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DECISION MAKING FOR LATE-PHASE RECOVERY FROM MAJOR NUCLEAR OR RADIOLOGICAL INCIDENTS

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National Council on Radiation Protection & Measurements

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Decision Making for Late-Phase Recovery from Major Nuclear or Radiological Incidents

Recommendations of the
NATIONAL COUNCIL ON RADIATION
PROTECTION AND MEASUREMENTS

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Preface

A major nuclear or radiological incident, caused by an act of terrorism or an accident, could have significant societal consequences, depending on the type and magnitude of the incident and circumstances specific to the local communities affected. Previous large-scale radiological or nuclear incidents, such as occurred at Chernobyl, Ukraine; Fukushima, Japan; and Goiânia, Brazil, have demonstrated the need for guidance on the long-term management of decontamination operations and waste disposition. In addition, large-area contamination could result from a terrorist attack involving a radiological dispersal device (*e.g.*, a dirty bomb) or an improvised nuclear device. Decisions about cleanup will depend on the scale to which society is adversely affected and the degree of stakeholder acceptance of the remediation goals.

The National Council on Radiation Protection and Measurements (NCRP) is providing this Report to offer guidance to those who will be responsible for managing cleanup and community restoration efforts. The Report considers optimization to be an iterative process that can be broken down into a series of steps, all of which involve close cooperation with stakeholders as a necessary element for a community-focused recovery effort. This guidance builds on previous recommendations from NCRP provided in the following reports:

- Report No. 138, *Management of Terrorist Events Involving Radioactive Material* (2001);
- Report No. 141, *Managing Potentially Radioactive Scrap Metal* (2002);
- Report No. 146, *Approaches to Risk Management in Remediation of Radioactively Contaminated Sites* (2004);
- Report No. 154, *Cesium-137 in the Environment: Radioecology and Approaches to Assessment and Management* (2006);
- Report No. 161, *Management of Persons Contaminated With Radionuclides* (2008);
- Report No. 165, *Responding to a Radiological or Nuclear Terrorism Incident: a Guide for Decision Makers* (2010); and
- Report No. 166, *Population Monitoring and Radionuclide Decorporation Following a Radiological or Nuclear Incident* (2010)

NCRP also published the Proceedings of the 1990 Annual Meeting entitled *Health and Ecological Implications of Radioactively Contaminated Environments* (1991).

This Report is intended to provide specific guidance to decision makers and policy setters in dealing with large-area contamination issues resulting from a terrorist attack or an accident, and is aimed particularly at local and regional elected officials rather than at radiation protection professionals. In particular, this Report addresses the following specific issues:

- development of a site-specific framework for optimizing decision making;
- involvement of stakeholders in the decision-making process; and
- management of long-term contamination and waste disposition strategies.

In addition, appendices provide detailed discussion of lesson learned from previous radiological and nuclear incidents, available decontamination techniques, economic analyses of various options, public information and risk communication, and current U.S. national guidance.

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John D. Boice, Jr.
President

Contents

1. Executive Summary

1.1 Introduction

In 2008 the U.S. Department of Homeland Security (DHS) published Protective Action Guides (PAGs) for radiological dispersal devices (RDDs) and improvised nuclear devices (INDs). Guidance was offered to protect members of the public in the early, intermediate and late phases of response to terrorist attacks with radiological devices. The optimization (of radiation protection)[1] process was recommended for late-phase recovery in circumstances of widespread contamination with radioactive material. The purpose of this Report is to provide guidance on optimizing decision making for late-phase recovery from a major RDD or IND incident. In light of the March 2011 Fukushima Dai-ichi Nuclear Power Plant (NPP) accident, the scope was expanded to include nuclear accidents.

A nuclear or radiological incident, caused by an act of terrorism or an accident, could have significant societal consequences, depending on the type and magnitude of the incident and circumstances specific to the local communities affected. The long-term impact of widespread contamination with radioactive material is an important concern. Highly populated metropolitan or economically sensitive regions will require an extensive cleanup effort, as evidenced by the 1986 Chernobyl nuclear reactor accident (IAEA, 2006a; 2006b; 2006c; UNSCEAR, 2011) and the 2011 Fukushima Dai-ichi NPP accident (ANS, 2012; GOJ, 2011; 2012; Gonzalez *et al.*, 2013; IAEA/NEFW, 2011; NDJ, 2012). Decisions about cleanup will depend on the scale to which society is adversely affected and the degree of stakeholder acceptance of the remediation goals (Chen and Tenforde, 2010; Eisenbud and Gesell, 1997; Eraker, 2004; Heintz, 2011; IAEA/NEFW, 2011; Porfiriev, 1999). Accomplishing remediation goals will require sound strategies and transparency. This Report examines the challenges faced in late-phase recovery following acts of terrorism (RDDs and INDs) or major NPP accidents with off-site contamination, and offers preparedness guidance to assist decision makers once the immediate crisis has come to an end.

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[1] In this Report, optimization refers to the optimization of radiation protection, that is, the balancing of benefits and costs of further reducing doses from radiation exposure.

After the initial response to a nuclear or radiological incident, it remains necessary to consider how best to use resources to reduce radiation exposures to individuals in the population. The broad aim is to ensure that the magnitude of the individual doses, the number of people exposed, and the likelihood of incurring exposures, are all kept as low as reasonably achievable (ALARA), economic and social factors being taken into account (the ALARA principle). If reducing radiation exposures can be achieved only by deploying resources that are not commensurate with the consequent reduction, it may not be in society's interest to take such additional steps, provided that individuals have been adequately protected (ICRP, 2007). The protection can then be said to be optimized and thus to have adhered to the ALARA principle. In such circumstances, the optimization process emerges as a balanced approach to address these very complex and intricate issues facing long-term recovery and the efficient recovery of affected communities.

Radiation protection, however, is not the only concern to be addressed in the management of long-term recovery. Recovery involves restoration of whole communities, including but not limited to infrastructures, public services, business and employment, as well as remediation of the contamination. Key considerations include public health and welfare, socioeconomics, waste management, environmental impacts, and communication.

Late-phase recovery needs to address radioactive contamination of large areas. Depending on the extent and magnitude of the contamination, as well as the possibility of it being caused by a terrorist incident, comparable remediation experiences from past or existing activities associated with cleanup of contaminated lands or facilities may not be readily applicable. For example the experience gained in addressing environmental contamination from nuclear weapons testing in years past is informative but not necessarily applicable to a particular accident or terrorist incident (Eisenbud and Gesell, 1997; IAEA, 1998; Robinson and Hamilton, 2010; Simon *et al.*, 2010; UNSCEAR, 1993). Similarly, statutory requirements under defined scopes and specific regulatory provisions may not always be suitable for wide-area contamination following a nuclear incident.

Concerns over terrorist attacks heightened after September 11, 2001, when four commercial airplanes were hijacked by terrorists and flown into the World Trade Center (WTC) buildings in New York City; the Pentagon in Washington, D.C.; and crashed into a field near Shanksville, Pennsylvania. Although no nuclear device or radiological sources were involved in these particular incidents, there has been a growing concern about the possibility, consequences, and state of readiness to manage such radiological incidents, including the development of countermeasures (DHS, 2008a; 2008b). Unlike examples of historical incidents involving nuclear reactor accidents, the absence of historical instances of radiological terrorist attacks limits the preparedness actions to postulated scenarios, such as those identified under the National Planning Scenarios for radiological and nuclear incidents (DHS, 2008b). National preparedness and resiliency is assessed, enhanced and improved by participation in large-scale exercises (DHS, 2007a; 2007b).

The two types of devices commonly considered in radiological terrorist planning scenarios are the RDD and IND. An RDD is any device that causes the purposeful dissemination of radioactive material with the intent to cause harm, but does not cause a nuclear detonation. An IND is an illicit nuclear weapon that is bought, stolen, or otherwise obtained from a nuclear state, or a weapon fabricated by a terrorist group from illegally obtained fissile nuclear weapons material that produces a nuclear explosion (DHS, 2008a). The RDD uses explosives for dispersal of radioactive materials and is commonly referred to as a "dirty bomb." In general, an RDD is considered to affect only a limited area and produce few casualties, mostly related to the explosion itself. However, under certain circumstances (related to the size, type and number of devices, and atmospheric conditions) an RDD has the potential to contaminate a large area as a result of dispersion. In contrast, a nuclear terrorism incident involving an IND would result in mass casualties, as well as causing widespread dispersion of fission products from fallout. More in-depth information concerning RDDs, INDs, and the emergency response phase of such incidents can be found in *Planning Guidance for Response to a Nuclear Detonation* (DHS, 2010a); National Council on Radiation Protection and Measurements (NCRP) Report No. 138, *Management of Terrorist Events Involving Radioactive Material* (NCRP, 2001); Commentary No. 19, *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism* (NCRP, 2005); Report No. 165, *Responding to a Radiological or Nuclear Terrorism Incident: A Guide for Decision Makers* (NCRP, 2010a); and Report No. 166, *Population Monitoring and Radionuclide Decorporation Following a Radiological or Nuclear Incident* (NCRP, 2010b).

Although a nuclear or radiological incident may lead to some initially high radiation doses to the responders and members of the public, long-term concerns are associated with the widespread contamination that may hinder the recovery effort. Much of the radiological preparedness and response efforts to date have focused on monitoring radiation levels and initial response, including triage and the medical screening of exposed or contaminated persons to determine their relative priority for treatment or decontamination.

The need to address systematically the long-term recovery of affected communities has been discussed (Chen and Tenforde, 2010; ICRP, 2009). The importance of the need for a comprehensive late-phase response to recovery was recently illustrated in the aftermath of the Fukushima Dai-ichi NPP accident of 2011 in Japan, where a sequence of natural disasters resulted in reactor meltdowns, radioactive releases, evacuation of the surrounding populations, and widespread contamination.

The purposes of this Report are to:

- present the general issues associated with late-phase recovery following an RDD or IND incident or a major NPP accident;
- identify and address important challenges facing decision makers and stakeholders; and
- develop a framework for a site-specific optimization process that provides a flexible and iterative approach to decision making that will facilitate recovery under complex societal circumstances.

1.2 Formulating Responses to Nuclear or Radiological Incidents

Emergency management activities related to industrial nuclear or radiological incidents have been underway in the United States for several decades. The PAG was developed by the U.S. Environmental Protection Agency (EPA) in the 1970s to facilitate protection of members of the public from potential radiation exposures during such incidents. Following the Three Mile Island (TMI) NPP accident on March 28, 1979, EPA was assigned the task of establishing exposure guidance that incorporated the lessons learned from TMI. EPA issued a manual of PAGs for radiological emergency response planning for nuclear incidents in 1992 (EPA, 1992), and issued an updated draft version of the PAG manual for public comment and interim use in March 2013 (EPA, 2013a). The final publication date of the new PAG manual was not available at the time this Report went to press.

After the September 11, 2001 terrorist attacks on the WTC and Pentagon, concerns that terrorist attacks could use nuclear or radiological devices led to the 2008 publication entitled *Planning Guidance for Protection and Recovery Following Radiological Dispersal Device (RDD) and Improvised Nuclear Device (IND) Incidents* (DHS, 2008a). This guidance, developed by experts across the federal government, provides PAGs to support decisions on actions to be taken to protect members of the public and emergency responders.

Both the PAG manual from EPA and the DHS Planning Guidance provide similar approaches and recommendations for protective actions during the early and intermediate phases of an incident. The DHS guidance also established an approach termed "site-specific optimization" that recognized the scope and complexity of late-phase decision making and recovery associated with radioactive contamination. The DHS guidance is consistent with the recommendations of NCRP and the International Commission on Radiological Protection (ICRP), which include optimization as one of the three principles of radiation protection, along with justification of planned activities or remedial actions, and application of dose limits to individuals. While "optimization" is not explicitly mentioned for late-phase recovery in the EPA draft PAG manual, the proposed approach contained flexible provisions for late-phase applications that are generally consistent with those recommended by DHS guidance.

In 2009 ICRP issued Publication 111, *Application of the Commission's Recommendations to the Protection of People Living in Long-Term Contaminated Areas After a Nuclear Accident or a Radiation Emergency* (ICRP, 2009). Drawing on the experiences and lessons learned from past incidents, this publication placed special emphasis on the optimization approach to late-phase recovery issues. When addressing optimization as a process, ICRP Publication 111 states "…while initially the exposures may be rather high and priority may be given to reducing the highest exposures, continuous efforts need to be made to reduce all exposures with time." The ICRP view is that optimization is not a one-time action to address late-phase issues, but rather a continuous, deliberate and iterative effort to manage radiation exposures to responders, remediation workers, and members of the public.

In 2011 the Federal Emergency Management Agency (FEMA) published the *National Disaster Recovery Framework* (NDRF) (FEMA, 2011a) to address recovery issues from major incidents involving all hazards, including natural disasters, accidents, and terrorist acts. Although important guidance and recommendations appear in the NDRF, it does not provide specific guidance for radioactive contamination.

1.3 Late-Phase Recovery: A Challenging Journey to Resume Normal Life

A major nuclear or radiological incident would result in considerable disruption and long-term impact on the affected communities, whether from an NPP accident or a terrorist attack involving an RDD or IND. Hundreds of thousands of citizens could face the possibility of evacuation or relocation during the early and intermediate phases of the response. The disruption of normal life could be prolonged and continue well into the late phase while awaiting appropriate remediation of the contaminated areas and/or specific policy decisions. Such long-term disruption was experienced after the Chernobyl nuclear reactor and Fukushima Dai-ichi NPP accidents where many thousands were evacuated, cities were abandoned, and many thousands will not be able to return to their homes and livelihood.

As learned from experience with past disasters, a robust recovery always depends on the resilience of the affected community. A resilient community is one that has the capacity to bounce back from a catastrophic impact to near-normal conditions in an expedient manner. Resiliency includes a willingness of the community to engage constructively with responsible authorities to achieve their common goals.

In addition to community resilience, a successful recovery requires ample resources in the form of financial, material and organizational support, and a well-structured operational recovery process with timely and transparent decision making. When a community is severely affected by a major incident, many key elements are seriously compromised. The recovery should focus on these elements to restore the functionality of the community and its economic and social health. Key elements include infrastructure (such as utilities, public transportation, communications, and food and water supplies), businesses (such as shopping centers, stores, and banks), employment, public services (such as government, security, medical, financial, public health, and education), and healthy environmental conditions. This multitude of complex and interrelated issues and priorities alone presents a challenging task that requires robust planning and response capabilities to restore the vitality of the affected communities in a timely and orderly manner. At the center of these issues following a radiological or nuclear incident is the urgent need to manage any widespread or potentially high radiation exposures to the population from dispersed radioactive materials. Given the recognized public fear of and anxiety associated with radiation (Bromet, 2014; Slovic, 2012), the effective mitigation of significant radiation exposures may well be one of the most important considerations in community restoration.

Actions important for late-phase recovery include the following, many of which require considerable deliberation and development *before* the occurrence of an incident:

- encourage a community-based recovery effort, and foster a collaborative culture among citizens' groups, business communities, government sectors, and all other stakeholders;
- develop a framework to define options and provide a basis for setting priorities and resolving conflicts that will arise, given the multitude of complex and interconnected issues to be faced;
- develop a transparent decision-making process and rationale to remediate wide-area contamination to facilitate recovery;
- formulate a clear strategy and approach to communicate benefits and risks of late-phase recovery options with stakeholders;
- develop a capability to identify and assemble information to manage available resources effectively;
- develop and maintain community resilience to respond and adapt effectively to the challenges and varying conditions inherent in any long-term recovery process;
- understand the consequences of implementing various remediation approaches and technologies so that options can be compared and selected in such a way to maximize the overall net benefit for the community;
- develop requisite expertise and effective administration of the various technologies that might be employed to remediate contaminated areas; and
- maintain a flexible approach to adapting strategies and decisions to accommodate developing and changing situations with an aim to reduce overall radiation exposures over time.

1.4 Optimizing Decision Making: A Framework and Process

For a nuclear or radiological incident, the primary goal of the entire recovery process will be to develop an agreed strategy for returning areas affected by the emergency to a state as close as possible to that existing before the release of radioactive material and restoring the population to a lifestyle where the accident is no longer a dominant influence. However, the approach to full recovery after an RDD or IND terrorist attack or NPP accident is likely to be multifaceted and highly complex. Consequently, setting priorities for particular decisions will inevitably involve trade-offs among many key factors and also will require comprehensive deliberations with multiple stakeholders to reach decisions.

The principles of radiation protection include justification, optimization and limitation (*i.e.*, the application of dose limits) (ICRP, 2007; NCRP, 1993). Optimization is closely aligned to the ALARA principle. Optimization recognizes the importance of these and other, nonradiation-related issues in framing the decision-making process for populations living in or returning to areas of widespread radioactive contamination (ICRP, 2009).

Remediation of contaminated areas will contribute to the complexity of issues facing a community. The late-phase recovery process begins with understanding and assessing current situations and evolves through characterizing and assessing potential impacts, from which the community goals and remediation options are identified and evaluated. Ultimately, decisions are reached and solutions implemented. Remediation work should be monitored and evaluated for success; adjustments should be made as necessary to respond to unforeseen challenges or opportunities. Through careful deliberation during the interactive process, and upon consulting with the stakeholders, decisions will need to be reached on such subjects as future land use, priority of remediation options, cleanup criteria, socio-political factors, cultural and ethnic issues, human health and public welfare needs, ecological risks, timeliness of cleanup, short- and long-term considerations, effective communication, decontamination technology, costs, and available resources and financing. Furthermore, it should be recognized that one of the inevitable products of widespread remediation efforts will be very large volumes of radioactive waste, the management of which could be a substantial challenge for any government or community.

Remediation of a very large area requires a huge labor pool and a substantial resource commitment, often at a national scale. Decisions must account for all competing factors discussed above to favor the overall well-being of the community in the long term. Although conventional experiences may be useful, their applicability to the specific situations affecting the community must be fully evaluated. For example, current cleanup operations under statutory regulatory provisions, although thorough and generally effective, require a lengthy process and may take up to decades to complete (GAO, 2012). Such a protracted timeframe would not be conducive to the goal of rapidly restoring the community's economic and social viability. Toward this end, DHS (2008a) PAG guidance is as follows:

> "Because of the extremely broad range of potential impacts that may occur from RDDs and INDs (*e.g.*, light contamination of one building to widespread destruction of a major metropolitan area), a pre-established numeric cleanup

> guideline is not recommended as best serving the needs of decision makers in the late phase. Rather, a process should be used to determine the societal objectives for expected land uses and the options and approaches available, in order to select the most acceptable criteria."

For late-phase response (*i.e.*, long-term cleanup), the guidance prescribes a long-term plan that properly balances site-specific circumstances. The primary goal of site-specific optimization is to establish societal objectives that, in addition to health protection, address future land use, cleanup options, technical feasibility, costs, cost-effectiveness, infrastructures, local economy, and public acceptance. Optimization is to be achieved by a flexible, iterative and multifaceted decision-making process that takes incident- and site-specific factors into consideration. For example, a small-scale incident may receive an expedited cleanup effort, while an incident causing extensive contamination (*e.g.*, affecting many city blocks in a major urban area) may require a considerable effort in terms of cost and time, thus influencing the decision on the final cleanup criteria for an acceptable level for remediation. In a wide-area contamination incident, it may not be practical or even possible to return the community and its infrastructures to pre-incident conditions; the resources available and technological capabilities may simply be insufficient to achieve the desired result. The alternative and perhaps only feasible approach is to manage mitigation efforts in an effective yet flexible manner toward a community-developed optimized level of protection (Longstaff *et al.*, 2010).

1.5 Stakeholder Engagement in Decision Making

A successful recovery effort is necessarily community-focused and community-based. Active participation by the stakeholders is an absolute necessity throughout the late-phase recovery process. In fact, individual, spontaneous efforts by citizens or community groups often take place before any assistance is provided by authorities or outside groups, as reflected in previous disasters including the recent Fukushima Dai-ichi NPP accident (Gonzalez *et al.*, 2013). The desire to take control and take action exhibited by citizens should be encouraged and supported and is essential to a community-based recovery. Community and stakeholder involvement should always remain central to the decision-making process.

Unlike emergency situations (*i.e.*, in the early phase), where prompt response toward preserving life and critical infrastructures is the overriding consideration, more time is available in the late phase to develop comprehensive and effective schemes for involving stakeholders in decision making. Considerations should include issues that are specific to local/regional needs, cultural/ethnic aspects, and justice/equity that involve the citizens of the affected communities.

Due to the complexity of the multi-faceted issues facing recovery, it is essential that preparations be made to bring stakeholders together for decision making in a way that maintains mutual trust and transparency. Planning for effective engagement with stakeholders should begin in pre-incident preparedness. Stakeholder groups representing the diversity of the community's needs and interests should be identified and engaged prior to the incident. Stakeholders who would be affected by a wide-area incident are generally not a single, monolithic group. They include many groups over a cross-section of the society with diverse backgrounds and differing perspectives. Although they share a common long-term goal for recovery (*i.e.*, a return to normality) individual short- and intermediate-term interests may be so conflicting as to render the decision-making process extremely challenging. For example, decisions regarding the location for storage and/or disposal of radioactive waste as well as cleanup standards and priorities will require exceptional stakeholder engagement. The effective coordination of diverse groups will be necessary to achieve consensus and avoid a protracted decision-making process. The timely implementation of the remediation strategy is essential under certain circumstances, particularly when a population has been displaced into temporary housing in a remote location.

In recognition of the limitations of the government's role and its effectiveness in responding to large-scale incidents, FEMA developed the "whole-community" concept in preparing for responses to a major disaster (FEMA, 2011b). This concept advocates continuous engagement and empowerment of stakeholders responding to disasters throughout all phases of the incident. Clearly, the integration of stakeholders into response actions has now become a central concept to drive an effective community recovery effort following a disaster.

Facilitating a meaningful and substantive integration of stakeholders into the decision-making process requires effective communication methods and the ability to accommodate feedback from stakeholders in a timely fashion. Guiding principles by which such a discourse and engagement can take place are available from the Congressionally-mandated Commission on Risk Assessment and Risk Management (Omenn *et al.*, 1997a; 1997b), the Health Physics Society (HPS, 2010), the International Radiation Protection

Association (IRPA, 2009), National Academies/National Research Council (NA/NRC, 2006; 2009), and NCRP (2004). These approaches emphasize positive and proactive interactions with stakeholders. They seek to develop a process conducive to resolving complex problems by collectively developing common objectives, while adhering to a common code of ethics.

The central principle for stakeholder engagement is a comprehensive communication effort that serves to foster a close partnership at every stage of the site-specific optimization process. This effort must include transparency, inclusiveness, shared accountability, and measures of effectiveness. Stakeholders must be fully informed of the objectives and processes of recovery because they will share in the outcomes. A detailed communication plan should be developed, adapted and improved throughout the entire recovery process. Stakeholders must participate in the iterative process of making decisions on risk management that begins with defining the problem and context, continues with risk analyses for various options, and ends with a decision on actions to be conducted.

As society evolves, so do the technologies for communication. The rapid developments in electronic technology and social media enable an expansion of communication mechanisms that were not previously available. The internet and advanced personal communication technology will continue to both encourage and require the exploration of new means of public communication and will serve an important role in expediting the otherwise complex and protracted decision-making process.

1.6 Managing Long-Term Contamination

A resilient community experiencing a major incident must possess several important attributes that include robust resources and adaptive capabilities to bring about a timely recovery. Unlike the nonradiological impacts that might be caused by natural disasters (such as earthquakes, tsunamis and hurricanes), a major nuclear or radiological incident will impose added concerns associated with widespread and long-term radioactive contamination. For radiological incidents, the recovery of the community will depend on developing a strategy and comprehensive plan for reducing residual contamination.

The site-specific optimization approach to reduce residual contamination from an RDD or IND incident or a major NPP accident necessarily involves long-term remediation strategies, through an iterative process. The strategies should comprise all activities undertaken to implement remediation actions and include a means to track the progress of the recovery activities. Further, it is important to evaluate the impacts of residual radioactive material on health and the environment, including food, water, commodities, properties, agriculture, and nonhuman biota.

Planning for long-term management should begin as soon as possible after the radiological incident has occurred. Actions taken during the early and intermediate phases, such as removing debris or storing the generated waste, may affect the available remediation strategies during the late phase. Around the end of the early phase, authorities should have a reasonable assessment of the magnitude of the incident and should be able to estimate the resources required to carry out long-term monitoring activities. During the intermediate phase, resources should be gathered and agreements and commitments for those resources should be completed. Monitoring throughout the process will include public health as well as environmental contamination, and should continue after the remediation effort has been completed and recovery has taken shape. Monitoring will help ensure that both long-term contamination (for residences, commercial properties, commodities, natural resources, and the environment) and public health (including physical and psychological status) issues continue to be addressed, while recognizing and mitigating any anxieties or stigma associated with radioactive contamination.

1.7 Path Forward and Recommendations

Given the potentially large magnitude and consequences of a nuclear or radiological incident, the traditional approaches to long-term recovery (specifically the remediation and cleanup of these contaminated areas), may not be applicable in either scope or approach. In such circumstances, the optimization process emerges as a balanced method to address the very complex and intricate issues facing long-term recovery. Besides protecting human health, the optimization process seeks to balance available resources and societal needs to determine priorities so that a path forward can be implemented for the efficient recovery of affected communities.

Preparation for a nuclear or radiological incident that will require substantial resources and commitments is not easily captured or incorporated into a general preparedness document. Quite often the affected communities may struggle to respond to and recover from an unprecedented situation that is far beyond their understanding. Consequently much more effort and emphasis is needed on community preparedness for late-phase recovery.

Valuable lessons have been learned from past NPP accidents such as Chernobyl in 1986 and Fukushima Dai-ichi in 2011. Both of these radiological incidents resulted in large contaminated areas with unprecedented environmental and economic consequences and numerous challenges and complexities (ANS, 2012; GOJ, 2011; 2012; Gonzalez *et al.*, 2013; IAEA, 2006a; IAEA/NEFW, 2011; ICRP, 2012; NDJ, 2012). A concerted international effort continues to compile and share the experience and information gained from these past incidents for future preparedness. Additionally, conducting exercises using multiple scenarios aimed to address specific societal concerns will produce additional knowledge that can help guide future decision making

After a catastrophic incident, a resilient community is one that is able to bounce back to near-normal conditions in an expedited manner. Recognizing that any response, especially for late-phase recovery, is incident- and site-specific, this Report emphasizes general principles for implementing the late-phase optimization process for circumstances that go well beyond those experienced in conventional cleanups. Important issues are identified that should be addressed more fully in years to come. These issues are enumerated in the following eight recommendations, and are discussed in Section 7:

1. Develop a national strategy to promote community resilience as the most favorable preparedness approach for responding to and recovering from nuclear or radiological incidents involving widespread contamination.
2. Integrate late-phase response into national, state and local government emergency response planning and ensure that it is regularly included in response exercises.
3. Embrace the site-specific optimization process for managing widespread contamination with radioactive material.
4. Ensure that stakeholder engagement and empowerment underpins the optimization process and uses consensus building in the decision-making process.
5. Develop a communication plan as an integral part of the preparedness strategy to ensure that messages are accurate, complete, understandable, and widely distributed
6. Develop adaptive and responsive cleanup and waste management strategies to facilitate the optimization process.
7. Conduct research to develop new technologies, methods and strategies that address remediation of wide-area contamination.
8. Establish a mechanism to integrate new information and lessons learned from past incidents into the strategies for late-phase recovery to promote continuous and adaptive improvements.

2. Introduction

2.1 Purpose

Federal agencies in the United States have been planning responses to nuclear emergencies for decades. Historically, the planning has focused on emergencies involving accidental releases of radioactive materials, such as from NPPs. Following the TMI accident in 1979, President Carter issued an executive order establishing FEMA as the lead agency for the nation's radiological emergency response and preparedness. Under that arrangement, EPA was assigned the task of establishing PAGs for radiological response planning. EPA, with input from other federal agencies, subsequently issued the *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (EPA, 1992).

The PAG manual[2] provides guidance for both the early and intermediate phases of nuclear incidents, but not the late phase; guidance for the late-phase response is mentioned to be forthcoming. These three distinct phases represent the timeline or evolution of an incident. Responses for early and intermediate phases require immediate attention to address emergency situations (such as rescuing survivors and containing worker and population exposures), while the late-phase actions require longer planning times and preparation to achieve a lasting and stable community recovery. The various phases of the response are accompanied by a recovery plan aimed at addressing the resilience of the affected communities (FEMA, 2011a). The recovery issues for the late phase entail remediation and restoration of the contaminated area. It is also important to initiate long-term surveillance and monitoring of the potential adverse health or environmental impacts due to radioactive contamination that may be present throughout the course of the incident and after.

In contrast to nuclear reactor accidents, the radiological response to emergency situations associated with terrorist acts has not been specifically considered or addressed until recently. Subsequent to

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[2] A revised draft PAG manual was issued by EPA in April 2013 for public comment and interim use. When finalized, this revised document will supersede the 1992 version. The final publication of the updated EPA document was not ready in time to be included in the discussion in this Report.

the terrorist attacks on September 11, 2001, many activities were undertaken, nationally and international, to address the response to and the management of malicious incidents involving the use of radioactive or nuclear material, although no RDD or IND terrorist incident has yet occurred.

Following the September 11, 2001 attacks, DHS was created by the Homeland Security Act of 2002, which consolidated 22 agencies (including FEMA) into one single federal agency. To address issues specific to potential terrorist attacks involving nuclear or radiological devices, DHS published its guidance in 2008 entitled *Planning Guidance for Protection and Recovery Following Radiological Dispersal Device (RDD) and Improvised Nuclear Device (IND) Incidents* (DHS, 2008a). This guidance provides PAGs to support decisions on actions to be undertaken to protect members of the public and emergency workers involved in the early and intermediate response phases, but no specific PAGs were prescribed for the late phase. Instead, the DHS-proposed approach involves a "site-specific optimization" process for developing appropriate remediation actions and the associated radiological criteria for the contaminated area. The approach to a full recovery for the late phase is likely to be multifaceted and involve a high level of complexity. For example, choosing and prioritizing any specific course of action will inevitably involve trade-offs among many key factors and also entail complex deliberations with stakeholders to achieve optimization.

Though the late-phase guidance developed by DHS offers a logical framework for the optimization process, it lacks specificity and technical detail on how to reach remediation decisions. In particular, given the complexity of a remediation decision and its dependence on site-specific factors, several issues critical to the decision-making process require more in-depth consideration. These issues include: updating the relevant policies and guidance, performing research, developing appropriate technology and methods, and adopting a holistic approach during recovery from an incident, all of which require extensive engagement of stakeholders in the process (Chen and Tenforde, 2010).

The objective of this Report is to establish a framework and approach for the decision-making process during late-phase recovery following an RDD or IND terrorist incident or a major NPP accident, based on the DHS guidance. The late-phase recovery issues to address include establishing priorities for remediation, decontaminating the affected communities, informing and involving stakeholders, and achieving a speedy and robust recovery.

This Report considers the application of optimization of radiation protection under the current DHS guidance, and is intended to be a resource for those individuals involved in late-phase recovery efforts. This Report is not intended to provide specific step-by-step instructions for a community because any preparation for or response to late-phase recovery is necessarily incident and site specific. Rather, this Report is intended to provide the basis for decision making, by clarifying the optimization process, identifying the essential elements of optimization, and providing guidance on approach and implementation.

2.2 Target Audiences

This Report is intended for those organizations and individuals at the local, regional, state, tribal and federal levels who are responsible for planning and executing late-phase actions following a nuclear or radiological terrorist incident, a major NPP accident, or other incidents resulting in wide-area radioactive contamination. This Report is also intended for those stakeholders who are concerned with the issues related to late-phase actions such as remediation of contamination caused by the incident. These individuals or organizations include the following:

- elected and appointed officials;
- lead and supporting agencies at all government levels;
- incident commanders;
- planners across disciplines that support emergency response;
- leaders of emergency response departments;
- managers of public health departments;
- managers responsible for providing assets and support;
- nongovernment organizations for disaster relief;
- municipal and business planners;
- community leaders;
- local recovery participants;
- concerned citizens; and
- other stakeholders who may be concerned with or interested in the related subjects.

2.3 Scope

The purpose of this Report is to develop a basis and framework for the optimization process to address decision making related to the late-phase response following a major incident or accident producing wide-area contamination. It also provides related information and methods of approach to the implementation of the process. The *late phase* follows the *early phase* and *intermediate phase* through the evolution of an incident; the phases have been designed to address specific characteristics of an incident, and accordingly, to formulate the proper responses. In an actual response, the three phases typically overlap each other in several ways and consideration of all phases during each individual phase is important.

The *early phase* (*emergency phase*) is the period starting from the initiation of an incident and lasting for the duration of the passing radioactive plume (a period that could generally last from a few hours to a few days depending on the incident), during which actual field measurement data are sparse. The main focus of the early-phase response is on the rescue mission and triaging the response to protect members of the public in the short term. During this time, external radiation exposure from the radioactive plume and the inhalation pathway for internal exposure are often the primary considerations for formulating protective actions such as sheltering in place or evacuation of personnel.

The *intermediate phase* (*recovery phase*) follows the early-phase response when radioactive material releases have been brought under control, and protective-action decisions can be made based on initial measurements of dose rates and contamination levels (FEMA, 2011a). The primary sources of population doses in this phase usually consist of external exposure from deposited radioactive contamination, inhalation of resuspended contaminants, and ingestion of foodstuffs with deposited radionuclides. The main objective of protective actions in the intermediate phase is to avoid or reduce such doses to affected populations, which may include interdiction of foods and relocation of some members of the public. The intermediate phase may last from weeks to months.

The *late phase* (*restoration phase*) begins with the initiation of restoration and remediation actions to reduce contamination of the environment and long-term doses to the affected populations, and may continue for years to decades. Applicable generic planning for successful disaster recovery has been documented in NDRF prepared by FEMA (2011a); however, the framework does not specifically address radiological incidents.

Responses to each individual phase should not be considered in isolation or as being independent of one another, but rather as being interrelated. For example, actions taken during the early phase, such as removing and clearing radioactive debris to facilitate rescue efforts, may affect decisions during late-phase cleanup actions. Likewise, some interim measures taken for decontamination of buildings or lands and removal of waste during the intermediate phase may also influence late-phase actions. Thus, it should be recognized that decisions made in any phase will not only have an immediate consequence but also affect what issues and decisions will need to be addressed in subsequent phases. Consequently, the interrelatedness of actions in different phases needs to be considered when planning for late-phase response actions.

The published DHS protective action guidance (DHS, 2008a) does not include specific criteria for late-phase actions because the uniqueness of each incident (type, size and location) would not lend itself to this approach. Instead, a decision-making process through the use of *optimization of radiation protection* has been recommended. Similarly, this Report also avoids listing specific step-by-step instructions, but rather establishes a basis and framework for the optimization process for decision making about late-phase response actions.

This Report clarifies and elaborates on the processes used to develop and implement procedures to optimize decision making for late-phase recovery that will expedite the establishment of cleanup goals on a site-specific basis. Additionally, this Report addresses several other issues important to the long-term recovery from nuclear or radiological incidents producing widespread contamination of populated areas. These special topics, all relevant to the optimization of the decision-making process, include cost-benefit analyses, radioactive waste management, risk assessment and communication, stakeholder interaction, and decontamination approaches and techniques. A concerted attempt has been made to incorporate the latest information available from the ongoing long-term recovery effort following the March 2011 incident at the Fukushima Dai-ichi NPP (GOJ, 2011; 2012).

2.4 Approach to Optimization

2.4.1 *Late-Phase Recovery Considerations*

One long-term consequence of a major radiological incident or NPP accident is the potential for widespread radioactive contamination of critical infrastructures, as well as public and private properties. The recovery effort will entail extensive planning and consideration of the various situations facing the communities adversely affected by the incident. Thus, an important consideration for communities is to determine an acceptable recovery level under which the daily routines that ensure essential economic activity and preserve the social fabric can safely resume, both in the short and long term. The optimization process that is advocated in this Report develops strategies to mitigate the residual contamination that are acceptable to stakeholders through a continuing iterative process. In addition, any post-mitigation concerns over residual contamination will be addressed by long-term monitoring and management to ensure the safety and protection of the population and the environment. Additional protective actions can be implemented for locations of higher residual contamination/radiation, such as administrative controls (*e.g.*, limiting access) or engineering controls (*e.g.*, turning soil or capping with uncontaminated material), to reduce the radiation exposure of people living, working or recreating in those areas. By considering all the available options and measures, optimization seeks to return the community to an acceptable normality in the most expedient manner.

Several other factors weigh heavily in the late-phase decision-making process, including the level of access to extensive resources and funding commitments, as well as acceptability of the recovery options and goals of stakeholders.

2.4.2 *Principle of Optimization of Radiation Protection: Approach and Implementation*

The principle of optimization (of radiation protection) has been advocated by international and national regulatory and advisory bodies and is also commonly practiced at all levels of governmental decision making. Of particular relevance is the ICRP advocacy of the principle of optimization, which maintains that the likelihood of exposure, the number of people exposed, and the magnitude of individual doses "should *all* be kept as low as reasonably achievable, taking into account economic and societal factors" (*i.e.*, the ALARA principle) (ICRP, 2007; NCRP, 1993; 2004). ICRP Publication 111 (ICRP, 2009) describes protection guidance for people living in long-term contaminated areas as an *existing exposure situation* [an exposure situation prescribed by ICRP (2007) for radiation protection against exposure under the existing conditions] as follows:

> "The Commission recommends that reference levels, set in terms of individual annual effective residual dose (mSv/year), should be used in conjunction with the planning and implementation of the optimisation process for exposures in existing exposure situations. The objective is to implement optimised protection strategies, or a progressive range of such strategies, which aim to reduce individual doses below the reference level."

In emergency or existing controllable exposure situations, the reference level represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimization of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration (ICRP, 2007). Further, ICRP (2009) goes on to state:

> "However, exposures below the reference level should not be ignored; they should also be assessed to ascertain whether protection is optimised or further protective actions are needed."

A key reason why no specific dose criteria have been recommended for late-phase recovery is that an array of site- and incident-specific considerations must be factored into the decision-making process. For example, a small-scale incident may be mitigated appropriately by an expedited cleanup effort, while an incident causing extensive contamination affecting many city blocks in a major urban area may warrant considerable effort in terms of costs and time. Therefore, it is not practical to use predetermined criteria for site cleanup and site restoration. Any criteria that are chosen will include consideration of existing statutory requirements on environmental remediation, along with other national and international recommendations. A range of other relevant criteria should also be considered, such as the extent and type of contamination, the technical feasibility of cleanup strategies, and their impact on human health and the environment. Furthermore, optimization will have to encompass additional factors beyond potential long-term health effects, including other priority issues facing the incident-disrupted population. These factors may include the local economy, healthcare services, critical infrastructures, transportation systems, public security and protection, and employment opportunities. Thus, the goal of optimization is meant to address the overall well-being of the affected society, rather than simply focusing on limited issues, such as potential long-term radiological health risks. This goal is consistent with the World Health Organization's (WHO) definition of health, which is, "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." (WHO, 1948).

The process of deliberation on remediation goals and criteria will be developed under the existing emergency management structure by emphasizing and incorporating in the decision-making process the appropriate technical entities and stakeholders who are pertinent to late-phase recovery issues.

2.5 Lessons Learned from Past Incidents

Though the late-phase guidance developed by DHS offers a logical framework for the optimization process, it lacks specificity and technical detail on how to reach remediation decisions. In particular, given that the complexity of remediation is highly dependent on site-specific factors, several issues that are critical to the decision-making process require more in-depth consideration. Because major incidents involving nuclear or radiological sources have been rare, one important aspect of this Report is to evaluate past incidents for their relevancy to the optimization issues discussed above and use them to provide realistic input to developing guidance for any future incidents.

Issues recognized and addressed in past incidents, with varying degrees of relevance, can be summarized as lessons identified or learned (Appendix A). Five categories of incidents are evaluated:

1. *incidents involving terrorist or clandestine acts* [*e.g.*, the poisoning of Alexander Litvinenko in London with ^{210}Po (Harrison *et al.*, 2007; The Times, 2006)];
2. *incidents involving nuclear facilities or sites* [*e.g.*, Chernobyl NPP in Ukraine (IAEA, 2006a; 2006b; UNSCEAR, 2011) and Fukushima Dai-ichi NPP in Japan (GOJ, 2011; 2012; Gonzales *et al.*, 2013)];
3. *atomic testing or military-related activities* [*e.g.*, Marshall Islands in the Pacific (Beck *et al.*, 2010; Eisenbud and Gesell, 1997); the Windscale fire in the United Kingdom (Wakeford, 2007); the loss of U.S. nuclear warheads near Palomares, Spain in 1966 (DOD, 1975; Iranzo *et al.*, 1987)];
4. *mishandling of medical sealed sources* [*e.g.*, Goiânia, Brazil in 1987) (IAEA, 1988)]; and
5. *recent planning exercises in the United States involving nuclear or radiological terrorism* [*e.g.*, DHS “top official” (TOPOFF) exercises (DHS, 2007a; 2007b), and the Liberty RadEx (LRE) exercise (EPA, 2010; 2011a)].

All these incidents involved varying degrees of radiological releases and contamination of the environment, some of which were more severe than others. In addition, three nonradiological cases are discussed:

- *natural disaster* [*e.g.*, Hurricane Katrina (Kates *et al.*, 2006)];
- *industrial accident* [*e.g.*, the Deepwater Horizon oil spill (OSC, 2011)]; and
- *act of terrorism* (*e.g.*, the collective terrorist attacks of September 11, 2001).

All these cases are described to illustrate the resilience of the affected communities, and the long-term, late-phase recovery efforts entailed in remediating the contaminated lands. In evaluating these incidents, special attention was paid to the nuclear accident in March 2011 at the Fukushima Dai-ichi NPP (under Category 2) (GOJ, 2011; 2012; Gonzales *et al.*, 2013; OECD/NEA, 2013) for which the recovery effort continues to provide lessons relevant to the issues discussed in this Report.

2.6 Relationship to Other NCRP Documents

This Report addresses issues associated with late-phase recovery specifically related to the long-term remediation of communities affected by major NPP accidents or radiological terrorist incidents. Recently published and relevant NCRP reports are:

- NCRP Report No. 138, *Management of Terrorist Events Involving Radioactive Material* (NCRP, 2001);
- NCRP Report No. 139, *Risk-Based Classification of Radioactive and Hazardous Chemical Wastes* (NCRP, 2002a);
- NCRP Report No. 146, *Approaches to Risk Management in Remediation of Radioactively Contaminated Sites* (NCRP, 2004);
- NCRP Commentary No. 19, *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism* (NCRP, 2005);
- NCRP Commentary No. 20, *Radiation Protection and Measurement Issues Related to Cargo Scanning with Accelerator-Produced High-Energy X Rays* (NCRP, 2007);
- NCRP Report No. 161, *Management of Persons Contaminated with Radionuclides* (NCRP, 2008a);
- NCRP Report No. 165, *Responding to a Radiological or Nuclear Terrorism Incident: A Guide for Decision Makers* (NCRP, 2010a); and
- NCRP Report No. 166, *Population Monitoring and Radionuclide Decorporation Following a Radiological or Nuclear Incident* (NCRP, 2010b).

These documents provide guidance on a spectrum of issues related to various stages of the response to nuclear or radiological incidents. In addition, NCRP Report No. 154, *Cesium-137 in the Environment: Radioecology and Approaches to Assessment and Management* (NCRP, 2006), provides detailed information on the distribution and transport of ^{137}Cs in the environment that is relevant for assessing incidents involving that radionuclide.

2.7 Report Structure

The following sections of this Report provide a basis and rationale for the framework and approach to the optimization process for late-phase recovery associated with major nuclear or radiological incidents that result in widespread contamination of populated areas.

- Section 3, Description of Major Nuclear or Radiological Incidents with Long-Term Contamination, provides general background information, radiological characteristics, and conditions regarding the late-phase recovery of an incident from either an accident or malevolent act.
- Section 4, Decision Framework in Late-Phase Recovery, discusses the basis and key elements for decision making in late-phase recovery actions. It lays out the radiation protection principles and emphasizes the principle of optimization as it pertains to late-phase recovery issues for protection of people living in contaminated areas under existing exposure situations. It also identifies the fundamental elements to be considered for optimization.
- Section 5, Implementation of the Optimization Framework for Decision Making, proposes a framework for optimization and furnishes a mechanism for its implementation.
- Section 6, Long-Term Management of Radioactive Contamination, describes the continued efforts required over time to ensure protection of affected populations and the environment as an integral component of the optimization process. Section 6 also discusses the long-term management of potentially-contaminated foodstuffs, drinking water, homes, farmlands, public places, and commodities.
- Section 7, Summary of Recommendations, summarizes key recommendations for late-phase recovery, which include:
    - updating existing policies;
    - improving understanding and communication of potential risks;
    - developing cost-effective technologies;
    - effectively engaging stakeholders;
    - conducting further research efforts; and
    - improving and building on the experience and information gleaned from the lessons learned.

  Such activities are vital to the preparedness for future incidents and thus form the basis for resiliency.

In addition, seven appendices (Appendix A through G) have been prepared with specific information to augment the individual sections and to assist readers in both the preparation and implementation of responses to relevant late-phase recovery issues.

In this Report, three similar radiation protection quantities are presented. Each refers to the quantity that was used in the source references for the situation being discussed. The quantities are: effective dose equivalent [as defined by ICRP (1977)], total effective dose equivalent (TEDE) [as defined by NRC (2014a)], and effective dose (as defined by ICRP (1991; 2007) and NCRP (1993)]. The technical formulations for each are given in the Glossary.

In this Report, the special names gray, sievert and becquerel for ionizing radiation units are used. The special names are also defined in the Glossary, along with conversions to the previous special units rad, rem and curie that are also used by some U.S. agencies.

3. Description of Major Nuclear or Radiological Incidents with Long-Term Contamination

3.1 Introduction

Major nuclear or radiological incidents may involve significant releases of radioactive materials and the subsequent contamination requires a remediation strategy to reduce the long-term exposures of affected populations.

A major incident involving a radiological source or nuclear device may cause severe radiological consequences to humans and the environment, both in the short and long term. Consequently such incidents will require a remediation strategy to reduce the long-term exposures of affected populations. Because, radiological or nuclear terrorist incidents have never occurred and major NPP accidents are rare, other major incidents can be instructive in understanding the nature of the consequences of such catastrophes and the difficulties associated with long-term cleanup. This section provides illustrative examples in two categories of incidents that may require remediation. Recently, attention has been given to the effects of RDDs and INDs in urban areas, summaries of which are also included.

The first category includes major accidents involving nuclear facilities (Section 3.2.1) and accidents involving radioactive materials or sealed sources (Section 3.2.2), and the second category involves malevolent acts, including terrorism (Section 3.3). The historic incidents discussed in this section resulted in widespread radioactive contamination, for which long-term remediation actions were required. Appendix A summarizes the lessons learned from many significant historic incidents that either affected, or had the potential to affect, large areas and populations.

3.2 Description of Major Historic Nuclear or Radiological Incidents

3.2.1 *Accidents Associated with Nuclear Facilities*

The following major nuclear facility accidents resulted in substantial releases of radioactive materials to the environment that required extensive remediation. The effects on the surrounding regions were long-lasting.

3.2.1.1 *Mayak Nuclear Facilities Accident: The Kyshtym Accident (1957).* Perhaps the most serious accident involving nonreactor operations occurred at the Chelybinsk-40 (also known as the Mayak Production Association) Plutonium Production Facility near Kyshtym in the former Soviet Union (Eisenbud and Gesell, 1997; ICRP, 2009). The releases from the accident contaminated an area the size of New Jersey with short and long half-life radionuclides. The accident caused both immediate casualties and long-term health impacts.

The accident occurred when the cooling system for underground high-level radioactive waste tanks failed, leading to overheating and an explosion on September 29, 1957. An estimated 100 PBq of radioactive material was released and traveled nearly 300 km (under calm wind conditions) and blanketed an area estimated at 15,000 to 23,000 km^2. Significant ground deposition of radioactive materials included ^{144}Ce, ^{144}Pr, ^{95}Zr, ^{95}Nb, ^{90}Sr, and ^{89}Sr. These radionuclides entered the food chain and resulted in the contamination of 10,000 tons of agricultural produce during the first 2 y after the accident. The high levels of released radioactive materials led to the evacuation of 10,730 people, with the maximally-exposed group of individuals receiving an average effective dose of ~520 mSv; the total estimated collective dose for the evacuated population was 1,300 person-Sv. There were 260,000 nonevacuated people living in areas with somewhat elevated contamination ranging from 4 to 70 kBq m^{-2}, with a collective dose estimated at 1,200 person-Sv (ICRP, 2009; UNSCEAR, 2008).

The discharge from the accident added further radioactive material to an environment that was already contaminated by chronic discharges from the operation of the facility prior to 1957. For example, from 1949 to 1956, an estimated 100 PBq of radioactive waste was discharged to the Techa River, because of an apparent lack of waste treatment facilities, and also from the storage of radioactive waste in open, unlined earthen reservoirs. External doses were from gamma rays emitted from ^{137}Cs, ^{106}Ru, and ^{95}Zr, while internal doses were mainly from the consumption of water and local foodstuffs contaminated with ^{89}Sr, ^{90}Sr, ^{137}Cs, and other radionuclides (UNSCEAR, 1993).

3.2.1.2 *Chernobyl Nuclear Reactor Accident (1986)*. The Chernobyl nuclear reactor accident, at Pripyat, Ukraine in April 1986, was the worst NPP accident in history. Following a massive steam explosion that destroyed Reactor Number 4, an estimated total of 14,100 PBq of radioactive material was released into the environment including 1,760 PBq of ^{131}I and 85 PBq of ^{137}Cs (ICRP, 2009; UNSCEAR, 2008; 2011). The initial explosion caused two deaths, 28 deaths occurred from acute radiation syndrome during the first four months (out of 134 patients treated for acute radiation syndrome), and an estimated 6,000 observed thyroid cancers (including 15 fatal cases by 2005) occurred among those who, as children, drank milk contaminated with ^{131}I (UNSCEAR, 2008; 2011). An estimated 336,000 people were evacuated within an extended "exclusion zone" of 4,300 km^2. An estimated 2.6×10^6 km^2 area of agricultural land was extensively contaminated. The releases affected parts of the western Soviet Union, the Ukraine, and Belarus, and to a much lesser extent the rest of Europe. Radioactive elements released from the reactor accident were measurable almost worldwide. More information about the long-term health effects and remediation of residual contamination continues to be obtained today, more than two decades after the accident (Appendix A.2.4).

3.2.1.3 *Fukushima Dai-ichi NPP Accident (2011)*. The Fukushima Dai-ichi NPP accident in March 2011 was the second worst NPP accident in history in terms of the amount of material released into the environment (OECD/NEI, 2013; UNEP, 2012; UNSCEAR, 2014). The accident occurred at the Fukushima Dai-ichi NPP when a 9.0 magnitude earthquake struck on March 11, 2011 and triggered a series of tsunamis, one of which was estimated to be 15 m high. The tsunamis disabled the station's on-site power and on-site emergency backup power systems. Due to the massive destruction all along the east coast of Japan, off-site electrical power and emergency equipment to provide cooling were unavailable for several days. The chain of incidents affected all six reactor units (Units 1 through 6), but proved to be particularly severe for Units 1 through 4. Partial core meltdowns occurred in Units 1, 2 and 3; the overheating of the fuels led to hydrogen explosions that destroyed the secondary reactor containment buildings for Units 1, 3 and 4; and another explosion damaged the Unit 2 containment. Additionally, there was concern over evaporation and reduction of the water level in the spent-fuel pools at Units 2, 3 and 4.

The release from the accident was estimated to include ~130 to 150 PBq of ^{131}I and 6.1 to 12 PBq of ^{137}Cs (GOJ, 2011; 2012).

The sum of activity from these two radionuclides was ~10 % of the activity released in the Chernobyl nuclear reactor accident; most of the released radioactive elements were toward the ocean and unpopulated areas. No workers or emergency responders received radiation doses high enough to result in immediate health effects. A total of 140,000 people were evacuated within a 30 km radius from the Fukushima Dai-ichi NPP. In addition, the earthquake and tsunami caused damage to hundreds of thousands of houses and other buildings and more than 400,000 people were displaced. This natural disaster, exacerbated by the Fukushima Dai-ichi NPP accident, is extraordinarily tragic in terms of its human toll (nearly 20,000 people died from the earthquake and tsunami). It is also considered one of the most economically devastating disasters in human history (UNEP, 2012).

Contamination was extensive within the 30 km exclusion zone, and very low, but above-background, radiation levels were detected as far south as Tokyo, ~220 km from Fukushima. A considerable amount of radionuclides was also discharged into the sea, raising concerns of contamination of oceanic flora and fauna. Remediation of the reactor units and the damaged facilities is still underway. Recovery efforts of surrounding areas have been underway and are expected to take many years to accomplish (Appendix A.2.1).

3.2.2 *Incidents Involving Radioactive Materials: The Goiânia Radiological Accident (1987)*

There have been several incidents involving sealed radioactive sources that led to uncontrolled dissemination of radioactive material that required subsequent remediation. One such incident which occurred in 1987 in Goiânia, Brazil involved an abandoned ^{137}Cs teletherapy source. The source was removed and ruptured by scavengers who were trying to reclaim the steel shielding for scrap metal but were unaware that they were dealing with a sealed radioactive source (IAEA, 1988).

About 86 % of the 51 TBq of ^{137}Cs in the form of cesium chloride was dispersed over an area of ~1 km^2 and required a significant remediation effort, which took months to complete. The total volume of waste generated for temporary storage amounted to ~3,134 m^3. The resulting radiation exposures caused four deaths from acute radiation syndrome and significant overexposures to several other people, including severe cutaneous injuries from direct contact with the dispersed cesium chloride powder (UNSCEAR, 2008) (Appendix A.2.3).

3.3 Nuclear or Radiological Incidents from Terrorist Acts

Unlike incidents involving nuclear fuel cycle or related operations, there has not been a widespread release of radioactive material from an act of terrorism. Consequently, preparation for any such incident must rely on postulated scenarios and a predictive approach to develop proper responses to such an incident.

However, there are a number of key differences between accidents and terrorist-initiated incidents:

- There may be little or no advance warning for a terrorist incident as opposed to the time typically required for nuclear facility conditions to degrade before an accidental release occurs.
- Nuclear facilities are often located well outside population centers and may include control zones around the facility to help mitigate the impact of a release, whereas terrorist incidents may take place anywhere, including densely populated urban areas.
- Nuclear facilities have well-established emergency action plans with requirements to conduct exercises on a regular basis, whereas a terrorist attack could occur in a location that is unprepared for a radiological incident.

3.3.1 *Radiological and Nuclear Terrorism*

There are hundreds of different radionuclides used in medicine, industry and research. Each of these has its own properties that affect how quickly the material decays, the ease of its detection, its overall health impact, and its remediation methods. Any of these could be used in an RDD.

A nuclear explosion is caused by an uncontrolled chain reaction that splits (fissions) nuclei of highly enriched uranium or plutonium, and produces an intense wave of heat, light, air pressure, and radiation, accompanied by the production and release of radioactive particles. The primary defense against a terrorist attack with a nuclear device is maintaining limited access to weapons-grade nuclear materials and carefully inventorying and guarding stockpiled weapons.

Another form of radiological terrorism could be the deployment of a radiation exposure device, where a radioactive source is hidden in a public area to expose those in its vicinity. An example is the November 1995 discovery of a capsule of ^{137}Cs in Moscow's Ismailovsky Park. However this scenario does not involve contamination and is not a focus of this Report.

3.3.1.1 *Radiological Dispersal Devices*. A device that spreads radioactive material with malicious intent is called a radiological dispersal device (RDD). An RDD that uses explosives for dispersion of the radioactive material is commonly referred to as a "dirty bomb," and is one type of RDD. Other types include nonexplosive release mechanisms such as sprayers (NCRP, 2001; 2010a).

A dirty bomb is *not* a nuclear device and does not involve a fission chain reaction or nuclear explosion. It is also *not* an NPP accident, around which much of the U.S. planning and radiological incident management has been built. A dirty bomb is unlikely to kill more people directly than an improvised explosive device that does not contain radioactive material. The use of radioactive material in a dirty bomb makes evacuating and treating victims more complex and also complicates the return of the affected area back to service. For this reason, RDDs have been popularly referred to as "weapons of mass *disruption*." The destruction may be well-localized, but the disruption of living conditions and the economic consequences could be significant without adequate preplanning for such incidents.

3.3.1.2 *Improvised Nuclear Devices*. The basic anatomy of a nuclear explosion is well known and documented (Glasstone and Dolan, 1977; NATO, 1996). Mitigating the impact of a nuclear explosion requires an understanding of key effects, which can be broken into two main components: prompt and delayed. As an example, the effects identified below are approximate for a 10 kT nuclear explosion. This yield is consistent with National Planning Scenario #1 (DHS, 2008b) and with the approximate yield of the nuclear weapons dropped on Hiroshima and Nagasaki.

Among prompt effects, the destructive blast is a major concern. The blast will damage or destroy most buildings within ~0.8 km of the detonation location and it is unlikely that the population in this area would survive. From ~0.8 to 1.6 km out, survival will most likely depend on the type of structure a person was in when the blast occurred. Even at ~1.6 km, the blast wave will have enough energy to overturn cars and severely damage light structures.

At ~1.6 km from the detonation, a person outdoors could get a significant exposure to the thermal pulse, which may cause burns to exposed skin; depending on weather conditions the thermal pulse could reach further than ~1.6 km. The lethal range of exposure to prompt gamma rays and neutrons is less than the range of lethal blast and thermal effects for a 10 kT detonation. Both thermal radiation and prompt nuclear radiation are significantly reduced for people inside buildings, depending on the structure and their location inside the structure.

Other prompt effects, such as electromagnetic pulse, which can disrupt communications and cause fires, also need to be considered in response planning. For a ground level detonation most electromagnetic pulse effects will be limited to within ~3.2 to 8 km with a few random, longer-range disruptions occurring further out. Although the possibility of a "firestorm" is unlikely given modern construction, there will be a large number of small, disparate fires started from thermal and blast effects (generally within ~1.6 km radius) which could spread and coalesce if not extinguished.

The primary delayed effect from a ground level nuclear detonation is from "fallout." Fallout is generated when the dust and debris excavated by the explosion is combined with radioactive material (both fission products and activated material) and drawn upward by the heat of the explosion. This cloud rapidly climbs through the atmosphere, up to ~8 km high for a 10 kT incident, and highly radioactive fission products coalesce and drop back down to Earth as the fireball cools. It is important to note that Hiroshima and Nagasaki did not have significant fallout because their detonations occurred high enough above the cities so that dust and debris from the ground did not have the opportunity to mix with the fission products.

The immediate hazard from fallout comes not from breathing the radioactive particles, but from being exposed to the ionizing radiation emitted by the radioactive materials that have settled on the ground and building roofs (Buddemeier and Dillon, 2009). Radiation levels from these particles will drop off quickly, with most (55 %) of the energy given off in the first hour and 80 % within the first day. Although it is highly dependent on weather conditions, the most dangerous concentrations of fallout particles (*i.e.*, potentially fatal to those outside) occur within ~32 km downwind of a 10 kT incident. Fallout particles are clearly visible as they fall, often the size of fine sand or table salt (NCRP, 1982). Even outside of this area in which fallout can be immediately dangerous to life and health, additional protective measures such as sheltering to reduce exposure, food embargo, and long-term population relocation may be warranted for hundreds of kilometers. These early- and intermediate-phase concerns will be primarily driven by short-lived radionuclides, whereas long-term recovery efforts will focus on the longer-lived radionuclides.

The damage caused by the blast and electromagnetic pulse will create damage to the urban and suburban infrastructures that can affect the recovery process. Electricity, communication, transportation, water, sewerage, and public health infrastructure may all need to be fully or partially restored to support the recovery process. It is important to recognize that critical infrastructure elements are interrelated. For example, if the blast causes water lines to rupture, as well as gas lines, the resulting gas-driven fires will be more difficult to extinguish without the necessary water pressure.

3.3.2 *Incident Progression and Radiological Characteristics*

3.3.2.1 *Incidents Associated with an RDD*

3.3.2.1.1 *Radioactive sources.* Many radionuclides used in medicine and industry do not pose a long-term remediation concern because of their short half-lives. For radionuclides with longer half-lives, the main issue for recovery planning is deciding on the cleanup level required, which will be influenced by the potential health hazard of the specific radionuclide(s) of concern.

In addition to external exposures, health effects may arise from inhaling or ingesting the radionuclide(s) from an RDD. Cleanup levels are driven by the radiation exposure that might occur to members of the public or workers in the vicinity of the residual radioactive material. The exposure, or estimated dose of radiation, is calculated assuming the possibility that radioactive material remaining in the area may be resuspended into the air and inhaled, or ingested following transfer *via* the food chain or directly from other surfaces such as a person's hands. Risk coefficients and dose coefficients for inhalation and ingestion are cataloged in federal and international guidance (Eckerman *et al.*, 1999; ICRP, 1995) and demonstrate how, for a given effective dose, the associated concentration of a radionuclide can vary by more than four orders of magnitude among different radionuclides.

According to NA/NRC (2008), "out of the thousands of manufactured radionuclides, ^{241}Am, ^{137}Cs, ^{60}Co, and ^{192}Ir account for nearly all (99%) of the sealed sources that present the highest security risk for the United States." The International Atomic Energy Agency (IAEA) has developed a categorization system for radioactive sources used in a wide range of applications in industry, medicine, agriculture, and research and education (IAEA, 2003). The applications of highest concern are radioisotope thermoelectric generators, industrial irradiators, medical teletherapy units, multibeam teletherapy (gamma knife) units, and industrial gamma-ray devices. These applications typically use beta-particle/gamma-ray-emitting radionuclides that have less biological effectiveness than alpha-particle emitters but are often used in significant quantities.

3.3.2.1.2 *Beta-particle/gamma-ray sources.* Most beta-particle/gamma-ray sources have the following general properties:

- can pose both an external and internal dose hazard;
- can be a hazard even without removable contamination;
- have a lower biological effectiveness than alpha-particle emitters; and
- are readily detected by measuring ambient radiation levels.

Cesium-137 is widely used in medicine and industry and is representative of a large category of commonly used beta-particle/gamma-ray-emitting radionuclides such as ^{60}Co and ^{192}Ir. The high-energy gamma ray emitted by this class of material can pose a significant external hazard, especially when the material is concentrated (*i.e.*, not dispersed). When sufficient material is present, ^{137}Cs can represent a hazard to an individual several meters away and the gamma-ray emissions can be readily detected much farther out. This means that heavy shielding would be required to safely move or conceal significant quantities of ^{137}Cs.

Although ^{137}Cs sources are most often encapsulated in stainless steel, the material itself is typically in the form of a powder (cesium chloride), making it both an external and internal hazard to individuals near a ruptured source. With a radioactive half-life of 30 y, reliance on natural decay is not an effective or practical means of remediation (NCRP, 2006).

3.3.2.1.3 *Alpha-particle sources*. Most alpha-particle sources have the following general properties:

- have to be taken into the body (through ingestion, inhalation or wounds) to be a hazard;
- are not a hazard without removable contamination;
- have a higher biological effectiveness than beta-particle/gamma-ray emitters; and
- are difficult to detect, and air sampling and surface contact methods are usually required for measurement.

For the purpose of remediation planning, alpha-particle-emitting radionuclides represent an important class of material. The intake of alpha-particle emitters under certain conditions can pose a significant radiological risk. Although the short range of alpha particles makes it difficult to detect at distances greater than a few centimeters in air, most commonly used alpha-particle emitters also have low-energy gamma rays and/or x rays associated with their decay, which improves the ability to detect them at a distance. This category of material is well represented by ^{241}Am, one of the most commonly used alpha-particle-emitting industrial sources. Common uses of this material include oil well logging, which may require an activity that uses 1.85×10^5 to 8.51×10^5 MBq of ^{241}Am in the form of americium-beryllium neutron sources, and laboratory calibration sources that can have up to 7.40×10^5 MBq of ^{241}Am.

3.3.2.1.4 *Radiopharmaceuticals and biomedical research radionuclides*. Some of the most commonly produced radionuclides are used for medical diagnosis, medical treatment, and/or biomedical research. Although these materials are widespread, they are generally transported and used in relatively small quantities and have short half-lives. Due to their short half-lives, an optimum approach to recovery from an incident involving these materials may simply be to wait until the material decays away. Table 3.1 lists several radionuclides commonly used in medicine and their half-lives.

3.3.2.1.5 *Dispersal characteristics*. For an RDD, the resulting contamination will depend on the radionuclide(s) used, their chemical and physical forms, the method of dispersal, and local weather conditions. Because of these factors a wide range of potential types of contamination should be considered for planning purposes.

Radioactive material dispersal incidents can range from those involving small and localized consequences to those involving a widespread impact to the environment with a footprint on the order of a few square kilometers and greater (Harper *et al*., 2007). Therefore preparedness measures should always be flexible and scalable, and well-understood by all neighboring jurisdictions within a threatened area.

In general, it is more likely that the consequences of an outdoor explosive dispersal of radioactive material will only affect a small area (*e.g.*, a few city blocks) but, similar to a chemical spill, care is needed to limit the spread of the material into other areas and prevent uncontaminated people from entering. It is expected that most exposures would be too low to cause acute radiation effects to people and, with the exception of severe injuries from the conventional explosion, the major consequence would be low-level contamination from gamma-ray sources and possibly significant psychosocial effects.

3.3.2.2 *Incidents Associated with an IND*

3.3.2.2.1 *Radionuclide concerns*. Although dangerous levels of fallout contamination drop off quickly in the first few days after the detonation of an IND, levels of contamination that require protective actions to reduce public exposure might extend for tens, if not hundreds, of kilometers and persist for years. The fallout contamination may contain hundreds of different radionuclides all decaying

TABLE 3.1—*Radionuclides commonly used in medicine and their associated radiation type and use.*

Radionuclide	Half-Life	Radiation Type and Use
Iodine-123 (^{123}I)	13.1 h	Iodine-123 is used in radiolabeled agents for imaging and as a thyroid diagnostic scanning agent.
Iodine-124 (^{124}I)	4.2 d	Positron (beta-particle) emitter used in positron emission tomography scans and medical investigational purposes.
Iodine-125 (^{125}I)	59.4 d	Beta-particle and low-energy gamma-ray emitter used in radioactive "seeds" for treatment of prostate cancer and used in biomedical research.
Iodine-131 (^{131}I)	8 d	Beta-particle/gamma-ray emitter used in the diagnosis and treatment of thyroid diseases.
Thallium-201 (^{201}Th)	72.9 h	Beta-particle/gamma-ray emitter used in myocardial perfusion imaging.
Technetium-99m (metastable) (^{99m}Tc)	6 h	Common beta-particle/ gamma-ray emitter used as a medical tracer derived from the beta-particle decay of ^{99}Mo.
Molybdenum-99 (^{99}Mo)	66 h	The ^{99}Mo source is in a sealed container, sometimes referred to as a "cow" from which the ^{99m}Tc isotope is "milked."
Phosphorus-32 (^{32}P)	14.3 d	Treatment of joint pain (radiosynovectomy) and polycythemia vera, and in uptake studies in plants and animals.
Palladium-103 (^{103}Pd)	17 d	Beta-particle and low-energy gamma-ray emitter used in radioactive "seeds" for cancer treatment, particularly prostate cancer.

at different rates. Due to this dynamic, predominant radionuclides will change with time. After a year, the dominant fission products will be ^{144}Ce, ^{95}Zr, ^{137}Cs, ^{89}Sr, and ^{90}Sr. There may be additional radionuclides created by neutron activation of elements such as ^{55}Fe and ^{60}Co, but this will depend on the environment in the immediate vicinity of the IND detonation. There may also be trace elements of the original fuel (*i.e.*, uranium and plutonium) as well as fuel activation products such as ^{239}Np and ^{237}U.

3.3.2.2.2 *Fallout characteristics*. Initially, the primary hazard from fallout is external gamma-ray and beta-particle exposure. A significant amount of energy is given off early as the short-lived radionuclides decay away and the significance of the external exposure pathway is reduced whereas internal exposure issues become more important. By the time late-phase restoration occurs, as discussed in Section 3.4, the inhalation and ingestion pathways can represent important contributors of potential doses to those using the lands or structures.

> NCRP 2001: "After the terrorist attack has occurred and the contaminated clouds have dissipated, the major pathways of concern are those arising from freshly deposited radioactive materials. These pathways are direct irradiation from deposited materials, inhalation of resuspended material, and ingestion of externally contaminated foodstuffs. In general, a large number of environmental radiation measurements should be obtained to characterize the areas of concern. Protective actions, such as relocation and food interdiction, may be imposed to avert some of the exposure to the public through these pathways."

There is likely to be extensive fallout from surface and near-surface detonations, while for airbursts the contamination will be much lower but may be more widely distributed.

Past experience of long-term contaminated areas resulting from either nuclear tests or nuclear accidents illustrates the importance of considering the potential for ingestion of contaminated foodstuffs several decades after the incident. Management of these foodstuffs to protect the local population against chronic internal exposure is essential (ICRP, 2009). When urban and semi-urban environments are affected, irradiation and inhalation may remain important exposure pathways for a long period of time (ICRP, 2009).

3.3.3 *Magnitude of Radioactive Contamination*

The exact magnitude of any impact from an RDD or IND would likely be associated with scenarios that are specific to the incident (*i.e.*, radioactive sources and detonation information) as well as incident location and site conditions (*i.e.*, weather conditions, affected populations, socio-economic situations). It is therefore difficult to characterize the magnitude of the impact from a particular incident involving RDDs or INDs. However, some existing systems, such as the International Nuclear and Radiological Event Scale (INES) (Appendix A), that were developed to characterize the severity of incidents at nuclear or radiological facilities, could be helpful in conveying an understanding of the magnitude of the impacts from RDDs or IND incidents, although not necessarily the health impacts from population exposures.

Simpler rating scales such as developing criteria for limited, modest, or large-scale incidents might also be developed to indicate the potential impacts from a terrorist incident. Regardless of the specific situation, each incident may cause considerable disruption, anxiety, and possible trauma to the affected society in the short term, and have long-lasting implications.

3.4 Incident Phases for Response and Recovery

A common misperception is that recovery begins after the response phase. However, these efforts are actually performed in parallel and represent similar and overlapping phases. Key federal doctrine that describes these phases includes:

- *Planning Guidance for Protection and Recovery Following Radiological Dispersal Device (RDD) and (IND) Incidents* (DHS, 2008a), abbreviated hereafter as “RDD/IND Planning Guidance.” This guidance largely adopts the early- and intermediate-phase guidance in the *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (EPA, 1992). As noted in Section 2, an updated draft of the EPA PAGs Manual was issued in early 2013 for interim use and public comment, but has not been finalized in time for incorporation into this Report. The phases in the RDD/IND Planning Guidance are described as:
    - early (hours to days);
    - intermediate (hours to weeks or months); and
    - late (weeks or months to years).
- *The National Disaster Recovery Framework* (NDRF) (FEMA, 2011a) is a companion document to the *National Response Framework* (NRF) (DHS, 2008b) and supersedes the previous Emergency Support Function #14 (ESF #14) (Long-Term Community Recovery). The phases in the NDRF are described as:

- short term (days);
- intermediate term (weeks to months); and
- long term (months to years).

These documents describe similar phases, but their foci and terminology are slightly different. Although phase timing is driven by the size and complexity of the incident, there is a slight mismatch between the timing of the phases described in the RDD/IND Planning Guidance and NDRF guide. The RDD/IND Planning Guidance phases start slightly earlier than the NDRF recovery phases with the similar name. This situation is further complicated by the fact that neither document defines a discrete transition. Rather the phases overlap so that intermediate-phase activities can occur while early- and/or late-phase activities are also being performed, as demonstrated in Figure 3.1. For the purposes of this Report, the RDD/IND and NDRF phases will be considered to be roughly equivalent, and subsequent sections will identify some of the major activities and recovery planning factors in the context of these phases.

Although this Report addresses the radiological aspects of the late-phase recovery from a major radiological incident, it is important to recognize that there are a number of nonradiological recovery activities that will also be important elements of the recovery process. The NDRF (FEMA, 2011a) provides guidance on recovery for all-hazard incidents. It describes the following recovery support functions that need to be considered for the recovery process for all large-scale incidents:

- community planning and capacity building;
- economic;
- health and social services;
- housing;
- infrastructure systems; and
- natural and cultural resources.

These related issues, together with radiological considerations, are to be considered in the decision making through the optimization process discussed in Sections 4 and 5.

3.4.1 *Phases of Incidents*

As noted above, the existing federal guidance documents (DHS, 2008a; EPA, 1992; FEMA, 2011a) identify three time phases for the response and recovery following a major radiological incident, but differ slightly.

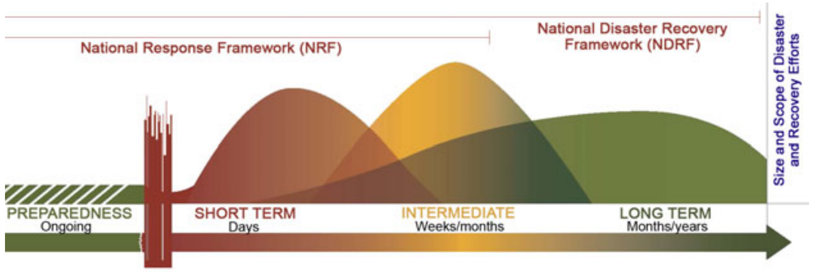

Fig. 3.1. Illustration of how response and recovery activity phases overlap (FEMA, 2011a).

3.4.1.1 *Short-Term Phase Contrasted with the Early Phase*. The initial response and recovery phase following an incident is the period in the first few hours or days of the incident when immediate actions may be required to save and sustain life, including actions to reduce or avoid radiation exposure to members of the public and responders. Actions in this period are likely to be conducted with minimal or incomplete information on the nature and extent of the incident.

> "The response during the early phase includes initial emergency response actions to protect public health and welfare in the short term, considering a time period for protective actions of hours to a few days. Priority should be given to life-saving and first-aid actions. In general, early phase protective actions should be taken very quickly, and the protective action decisions can be modified later as more information becomes available" (DHS, 2008a).

> "Short-Term Recovery – Phase of recovery which addresses the health and safety needs beyond rescue, the assessment of the scope of damages and needs, the restoration of basic infrastructure and the mobilization of recovery organizations and resources including restarting and/or restoring essential services for recovery decisionmaking" (FEMA, 2011a).

3.4.1.2 *Intermediate Phase Contrasted with the Intermediate Phase*. As the incident is stabilized, it will transition to the next phase which typically occurs in the "days to weeks" range, but can follow the early-phase response within as little as a few hours. Although protective actions may still be required in the intermediate phase to reduce or avoid radiation exposure, immediate threats to public safety have been controlled and the general nature and extent of the incident have been largely established. Typical actions during the intermediate phase are to conduct more detailed characterization monitoring, agricultural embargos, and a deliberate relocation of residents if warranted.

> "The intermediate phase of the response is usually assumed to begin after the incident source and releases have been brought under control and protective action decisions can be made based on measurements of exposure and radioactive materials that have been deposited as a result of the incident. Activities in this phase typically overlap with early and late phase activities, and may continue for weeks to many months, until protective actions can be terminated" (DHS, 2008a).

> "Intermediate Recovery – Phase of recovery which involves returning individuals, families, critical infrastructure and essential government or commercial services to a functional, if not pre-disaster, state. Such activities are often characterized by temporary actions that provide a bridge to permanent measures" (FEMA, 2011a).

Although the geographic areas that require protective action in the early phase are fairly limited, the areas for intermediate-phase activities are much more extensive.

3.4.1.3 *Long-Term Phase Contrasted with the Late Phase*. The objective of the long-term phase is to revitalize, rebuild and repopulate affected areas, including recovery of contaminated areas through the site-specific optimization process described in the RDD/IND Planning Guidance. Appropriate cleanup (or clearance) levels and priorities will be established through a process that includes broad stakeholder input and sound risk management principles.

> "With additional time and increased understanding of the situation, there will be opportunities to involve key stakeholders in providing sound, cost-effective cleanup recommendations that are protective" (DHS, 2008a).

> "Long-Term Recovery – Phase of recovery that may continue for months or years and addresses complete redevelopment and revitalization of the impacted area, rebuilding or relocating damaged or destroyed social, economic, natural and built environments and a move to self-sufficiency, sustainability and resilience" (FEMA, 2011a).

3.4.2 *Protective Actions*

3.4.2.1 *Protective Action Guides*. A PAG gives the projected dose (to an individual) from an unplanned release of radioactive material at which a specific protective action to reduce or avoid that dose is warranted. For example, the early-phase PAG for evacuation/sheltering-in-place (nominally a period of 4 d) is as low as 10 mSv total effective dose equivalent (TEDE). This criterion means that if the projected dose is *expected* to be >10 mSv during the first 4 d, shelter-in-place or evacuation of the potentially-exposed population should be considered.

The following guidance is extracted directly from the EPA *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (EPA, 1992):

> "The PAGs are intended for general use to protect all of the individuals in an exposed population."
>
> "PAGs … do not represent the boundary between safe and unsafe conditions; rather, they are the approximate levels at which the associated protective actions are justified."

The current draft guidance (EPA, 2013a) makes similar statements about PAGs:

> "They are not meant to be applied as strict numeric criteria, but rather as guidelines to be considered in the context of incident-specific factors. PAGs do not establish an acceptable level of risk for normal, nonemergency conditions, nor do they represent the boundary between safe and unsafe conditions."

3.4.2.2 *Early-Phase Protection Action Guides*. The Federal Register Notice, *Protective Action Guides for Radiological Dispersion Device (RDD) and Improvised Nuclear Device (IND) Incidents* [FR Vol. 73, No. 149, August 1, 2008, (DHS, 2008a)] provides initial guidance for potential exposure levels that warrant protective measures. The guidance was developed primarily to help balance the risk of exposure to low levels of radiation (and the associated slight increase in cancer risk) with the hazards of actions, such as sheltering or evacuation. Early-phase PAGs are shown in Table 3.2. Although this Report focuses on recovery issues, the PAGs can help define areas where initial actions may set important social perceptions of these areas.

3.4.2.3 *Intermediate-Phase PAGs*. The exposure pathways of concern during the intermediate phase are direct (external) exposure

TABLE 3.2—*Early-phase PAGs for sheltering-in-place or evacuation of members of the public (DHS, 2008a).*

Protective Action	Projected Dose Averted	Comments
Sheltering-in-place or evacuation of members of the public, whichever results in the lowest exposure.	10 – 50 mSv (outdoor, 96 h exposure)	Should normally begin at 10 mSv; take whichever action (or combination of actions) that results in the lowest exposure for the majority of the population. Sheltering may begin at lower levels if advantageous.

from deposited radionuclides, inhalation of deposited radionuclides that become resuspended into the air, and ingestion of radionuclides (*e.g.*, *via* water, crops, milk, and food animals).

In an incident involving fission products (*e.g.*, reactor accident or nuclear yield from a weapon or IND), external exposure from deposited gamma-ray emitters is expected to be the primary concern. In an incident involving a fire or non-nuclear explosion of nuclear weapons or special nuclear materials, inhalation of resuspended contamination is likely to be the primary concern during the intermediate phase.

Protective actions taken during the intermediate phase will consist of relocation of the affected population and/or application of dose reduction techniques in addition to food and water restrictions. To implement these protective actions it is important to:

- establish a control zone, where relocation is warranted because projected first-year doses are estimated to exceed the relocation PAGs of Table 3.3; and
- adjust the control zone (as necessary) to meet the long-term objectives (second year and over 50 y) of Table 3.3.

3.4.2.4 *Late-Phase Site-Specific Optimization*. The objective of the long-term restoration phase is to revitalize, rebuild and revive affected areas, including remediation of contaminated areas through the optimization process described in RDD/IND Planning Guidance (DHS, 2008a). Appropriate cleanup (or clearance) levels and priorities will be established through a process that includes broad community stakeholder input and sound risk management principles to maintain the health of the affected population by

TABLE 3.3—*Intermediate-phase PAGs.*

Protective Action	Protective Action Guidance
Relocation of members of the public	20 mSv projected dose first year. Subsequent years 5 mSv y^{-1} projected dose.[a]
Food interdiction	5 mSv projected dose, or 50 mSv to any individual organ or tissue in the first year, whichever is limiting.[b]
Drinking water interdiction[c]	5 mSv projected dose in the first year.

[a] Persons previously evacuated from areas outside the relocation zone defined by this PAG may return to occupy their residences. Cases involving relocation of persons at high risk from such action (relocation) (*e.g.*, patients under intensive care) should be evaluated individually.

[b] FDA (1998).

[c] DHS (2008a).

ensuring a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. As indicated in Figure 3.1, some long-term activities begin early, even within the first few days after the incident. RDD/IND Planning Guidance recommends establishing a stakeholder working group and technical working group to help guide and prioritize the recovery process.

The RDD/IND Planning Guidance does not include specific cleanup criteria for RDD or IND incidents. Rather it recommends that decisions for late-phase response be made using a site-specific optimization process which is a decision-making process intended to take into account the many potential attributes or factors that can affect overall public welfare and restoration decisions. The subject of optimization is further discussed in Sections 4 and 5.

4. Decision Framework in Late-Phase Recovery

4.1 Late-Phase Recovery

4.1.1 *Objective of Recovery*

For a severely affected community, the objective of the long-term recovery is to return the community to an acceptable new normality in the most expedient manner possible, with a goal to re-establish and sustain the local economic and social viability.

Following a major nuclear or radiological incident, radiological responses for the emergency phases are implemented in accordance with appropriate PAGs, as discussed in Section 3. Almost parallel to these actions, the late-phase recovery effort begins with the ultimate aim to return the affected populations to an acceptable new normality, in which the communities can be functional and sustainable. Large segments of the population could be displaced, so communities will likely have a sense of urgency to start the recovery effort as soon as possible by implementing a concerted effort to address long-term recovery issues in order to repatriate those affected.

4.1.2 *Late-Phase Considerations*

While early and intermediate phases are emergency situations for which the time between decisions and actions is relatively short, the late-phase issues are nonemergent and therefore allow more time to plan and design appropriate approaches and actions. However, the magnitude and complexity of the late-phase issues increases substantially if radioactive contamination was widespread and affected a sizable segment of the population. Thus, while the efforts under the emergency situations address the urgent short-term needs following an incident, late-phase recovery focuses on restoring the functionality of the community, including the vitality of the local economy.

A successful recovery effort is predicated on proper remediation of the radioactive contamination; consequently any decision on recovery must address the contamination situation in shared decision making and action planning. For widespread contamination, this likely means identifying and resolving numerous radiological issues that are unprecedented for the community. These may include cleaning up an extended land area, storing and disposing of large amounts of radioactive waste, and addressing elevated dose levels to a large population.

4.1.3 *Resilience of Recovery*

For a region adversely affected by a disruptive incident, the ultimate recovery would be defined by the return of the communities to a state of normality. The term *resilience* has the following definition: "the capacity of a system to absorb disturbance, undergo change, and retain the same essential functions, structure, identity, and feedbacks" (Longstaff *et al.*, 2010). Resilience is measured by a combination of *resource robustness* and the *adaptive capability* of the community during response to the incident. A community's resource robustness is a function of the availability of resources including financial support, sufficient human resources with skilled workers, accessibility to relevant technologies, and a sound organizational structure. The community must also exhibit a strong desire and will to recover. A community's adaptive capacity is a function of the ability of individuals and groups to:

- store and *remember* experiences;
- use that memory and experience to learn, *innovate*, and reorganize resources to adapt to changing environmental demands; and
- *connect* with others inside and outside the community to communicate experiences and lessons learned, self-organize or reorganize in the absence of direction, and obtain resources from outside sources (Longstaff *et al.*, 2010).

Highly resilient communities with resource robustness, adaptive capability, and the will to recover do so much more quickly than low resilience communities lacking one or more of these elements. The will to recover can be amplified by political, economic and cultural factors and become the primary "driver" toward recovery with each factor contributing to the collective desire of the community to return to a normal life.

Figure 4.1 presents a conceptual illustration for the effect of resilience in the time following a disaster. In this figure, a community with a high degree of resiliency would experience a speedier and more robust recovery (the upper curve) compared with one that is less resilient (the lower curve) (*i.e.*, a community with a high degree of resiliency experiences a much smaller impact and shorter disruption from the same incident). All communities must devise

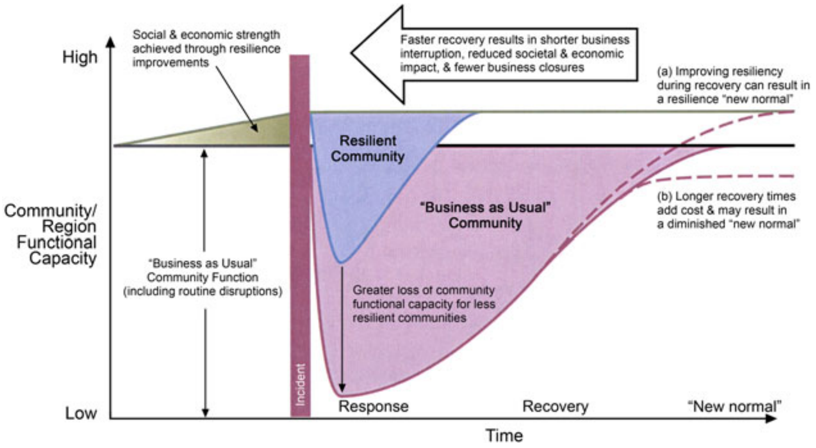

Fig. 4.1. Conceptual illustration of community resiliency in recovering from a disaster (adapted from CARRI, 2011).

and accept a path towards normality after a disaster and the more resilient communities get there quicker (CARRI, 2011). It is important to note that, with proper preparedness, such as strengthening the support infrastructure and better public awareness and training, a community can substantially strengthen its overall resiliency prior to an incident.

4.2 Key Issues in Late-Phase Recovery

The various phases of the response to a radiological terrorist act or major nuclear reactor accident are accompanied by a plan for recovery in which the effort involved in each phase aims to improve community resiliency and hasten the long-term recovery of the society (FEMA, 2011a). As stated in the NDRF (FEMA, 2011b), the recovery process is described as "a sequence of interdependent and often concurrent activities that progressively advance a community toward a successful recovery." As such, all response actions throughout the course of an incident need to be closely coordinated to achieve the ultimate goal of recovery. The long-term recovery should address all issues of community well-being such as *public health and safety*, the *local economy* (*e.g.*, creating and sustaining businesses and employment opportunities), *critical infrastructures* (*e.g.*, restoring utilities, public transportation, communication systems, food and water supplies), and *key public services* (*e.g.*, government services, security functions, healthcare, financial transactions, and education). These issues are discussed below, bearing in mind that all the related actions will be predicated on a set of acceptable mitigation criteria and associated actions to remove or reduce radioactive contamination resulting from the incident.

4.2.1 *Issues Affecting the Society*

The primary objective of late-phase recovery actions is to establish a new normality for the affected society, in the face of likely long-term physical and psychosocial sequelae (Appendix A). "Normality" in this context is a composite of interconnected health, safety, economic, infrastructural and sociopolitical elements. Funding the recovery will become a major consideration as options for remediation decisions are identified and their risks are characterized; a key component for decision makers will be *who pays* for the remediation and *how much* funding is available. There will be funding resources such as American Nuclear Insurers, the Price-Anderson Act, and the Robert T. Stafford Disaster Relief and Emergency Assistance Act (*i.e.*, the Stafford Act) (McCarthy, 2011), but they will not be unlimited and may not be accessible for all types of incidents. Stakeholders and decision makers need to decide what actions to take and what resources to commit as part of the site-specific optimization process.

Re-establishing local or regional economic viability is critical for late-phase optimization efforts. The timeframe for this depends on numerous factors relating to the precipitating incident (Section 3) that will determine the pace at which affected communities can be rebuilt and repopulated. Psychosocial effects may significantly contribute to poor long-term economic outcomes. Modeling response to an RDD terrorist attack, for example, suggests that behavioral effects stemming from fear and risk avoidance may affect both the willingness to pay for restoration and also increase the cost of supplies and/or other resources delivered to an affected region. In addition, those outside the affected area may be reluctant to purchase commodities originating in the affected zone (*i.e.*, stigma). These long-term behavioral effects can generate adverse changes in a region's gross domestic product that far exceed those caused by the incident's effects on resource supply (Giesecke *et al.*, 2012). Consequently, restoration of economic viability in affected regions has been among the most significant challenges following past radiological/nuclear accidents (Steinhausler, 2005). A major challenge in economic restoration is overcoming the stigma attached to radiation (Remennick, 2002; Slovic, 2012; Slovic *et al.*, 1991) and, by extension, to the populations, goods and services from regions where the incident occurred. Inadequate economic restoration may lead to permanent outmigration (for reasons apart from health-related considerations), as residents move elsewhere to seek gainful employment. Depending on the pre-incident economy of the affected locality (*e.g.*, a large city with a heavy industrial base), these dynamics can have considerable long-term effects on regional and national economies.

Reconstruction of physical infrastructure (*e.g.*, rebuilding of housing) is also a complex and challenging long-term ingredient of recovery-phase efforts (Kates *et al.*, 2006), as demonstrated by natural disasters such as Hurricane Katrina. Based on historical analysis, researchers had estimated that it would take 8 to 11 y to complete the reconstruction in New Orleans (Kates *et al.*, 2006). While the onset of restoration of essential services (*e.g.*, electricity, fuel supplies, hospital services) precedes the reconstruction phase, these essential activities can and typically do overlap (Kates *et al.*, 2006). However, following a major nuclear or radiological terrorism incident, the viable time-to-onset of these restoration and reconstruction activities may vary considerably depending on the radionuclide(s) involved, the scale and nature of their dissemination, and attendant health and safety considerations.

Sociopolitical issues are critical to consider in formulating recovery-phase actions. These include the political environment at the local, regional and national levels and how societies perceive its effectiveness. Research on societal dynamics following a radiological accident has characterized the restoration effort as the result of a series of processes that an affected society must experience sequentially and fully (Lochard and Pretre, 1995). These processes include, in order: *reflex* (acute post-incident delivery of preplanned interventions), *heroism* (dramatic measures taken to save lives and eliminate acute dangers), *acceptance* (a symbolization process around victims and heroes as the basis for collective memory, along with controlling of residual threats and progressive environmental rehabilitation), *mourning* (by survivors and the rest of the society), and *return to normality* (a symbolic and rational integration of the incident's consequences, yielding a re-establishment of normality).

While this sequence represents an ideal trajectory from incident to recovery, societal restoration may be adversely affected by factors such as stigmatization of individuals living in zones with higher levels of ground contamination. In such cases, the *acceptance* phase in this model would be replaced by a *revolt* phase among stigmatized populations, leading to *depression* and a post-incident psychosocial *crisis* among those most directly affected. Thus, effective restoration to normality following a major radiological incident requires explicit efforts at all levels of government to:

- "arrive, as soon as reasonably achievable, at a situation considered normal by the largest majority of the affected population"; and
- reduce the probability of a post-incident psychosocial crisis (or mitigating its impact if it does occur) among the population segments most directly affected by the original precipitating incident (Lochard and Pretre, 1995).

4.2.2 *Issues Related to Radioactive Contamination*

After a major nuclear or radiological incident, many, if not most, of the issues faced by the affected communities relate to the resulting radioactive contamination and the effectiveness of removal and mitigation efforts. Decisions about cleanup involve a number of considerations including:

- accurate knowledge of the extent and nature of the contamination;
- available technologies for cleanup and their efficacy;
- radiation protection issues and standards or guidance;
- generation and storage of radioactive waste;
- available resources; and
- acceptance by stakeholders.

Another issue is the possible reluctance of some people to return to a contaminated area with residual radioactive material that might also involve behavioral changes such as modifying diets, habits, livelihoods, or other lifestyle factors. Some people may be willing to take these measures for the chance to return to their homes but others may not. The decision to return may depend on each individual's perception of the risks and benefits involved and their own particular circumstances.

4.2.2.1 *Addressing a Multitude of Radiological Issues*. Strategies are needed that address different environmental exposure sources (air, water and land), multiple exposure scenarios (*e.g.*, residence, industry, farm, office, school), multiple pathways (direct gamma rays, inhalation, ingestion), and multiple radionuclides with different emissions (alpha particles, beta particle, and gamma rays), half-lives, and retention times in the body. Traditional cleanup practices conducted under much simpler circumstances and constraints may not be very informative in the case of multiple contamination and exposure circumstances. The community will likely continue to cope with the contamination in general, notwithstanding the cleanup efforts performed in selected priority locations. In addition, the varying health risks for people of different ages, genders, and underlying health status can complicate decision making, planning, and action implementation. Radiological issues that could further exacerbate the already-complex decision-making process are discussed below.

4.2.2.2 *Management of Radioactive Waste*

> Large quantities of radioactive waste will be generated in a major nuclear or radiological incident; handling these waste materials is a major challenge for the cleanup effort.

Radioactive waste generated by a major nuclear or radiological terrorist incident can result from direct radioactive contamination, deposition from the radioactive plume, or induction by prompt radiations (such as neutrons in an IND incident) on lands, buildings or properties (DHS, 2008a). In addition, radioactive waste will be generated during the decontamination and remediation processes.

The type and amount of waste generated will vary depending on the radioactive sources, environmental conditions, cleanup technologies available, level of cleanup goals, and the specifics of the sites involved. The waste will need to be properly characterized, packaged, stored and transported for disposal in a timely manner.

Potential waste volumes could be overwhelming. For example, the Japanese authorities managing the response to the Fukushima Dai-ichi NPP accident have estimated that between 5×10^6 and 29×10^6 m^3 of contaminated material will be generated from the cleanup, depending on the extent of agricultural and forest decontamination and on the annual target doses selected for various areas. To put this quantity of waste into perspective, a 1,000 MW(e) NPP typically generates a total of 15,000 to 25,000 m^3 of low-level radioactive waste (LLRW) during 60 y of operation (GOJ, 2011; 2012). This comparison demonstrates two important points about waste management during recovery from an unprecedentedly large radioactive contamination incident:

- waste volumes could range from well beyond the thousands of cubic meters typical of routine NPP operations to millions of cubic meters; and
- large waste volumes will have to be managed in extremely short timeframes compared to the 40 to 80 y operational lifetime of an NPP.

4.2.2.2.1 *Issues associated with existing systems for management of radioactive waste*. The complexities of managing radioactive waste following a major nuclear or radiological incident could be magnified by the acknowledged shortcomings in the nation's existing approach to handling and disposal of LLRW. Primary among the shortcomings is that the current U.S. regulatory approach to LLRW classification and disposal is origin-based rather than risk-based (NCRP, 2002a). This approach is inappropriate when ownership of radioactive waste is brought into question in the case of terrorist attacks, as discussed below. Concerns include the inability or difficulty to streamline the handling of very low-activity waste within the existing regulatory system, including the inability to exempt some exceptionally low-level waste from being considered as radioactive waste requiring remediation efforts (NA/NRC, 2006). Ideally, the regulatory and operational framework for managing these wastes would be driven by considerations of health risks to members of the public rather than by the origin of the waste (NCRP, 2002a). The existing U.S. waste classification system presents some regulatory rigidity that would be apparent in a large-scale contamination incident from an RDD, IND, or NPP, where great latitude of operational flexibility would be desired.

As demonstrated by the Fukushima Dai-ichi NPP accident, waste management and disposal is central among all the very difficult and challenging issues surrounding cleanup of widespread radioactive contamination. Effectively designing and implementing a robust waste disposal plan that uses the available infrastructure is critical to progressing in a responsible and efficient manner toward recovery, and the plan must be expeditiously established by authorities. The post-incident waste management approach will require broad support from the affected communities and take into account all waste disposal capabilities and considerations. Finally, including non-LLRW disposal options in the overall waste management approach will require thorough policy debate and policy modifications as needed.

4.2.2.2.2 *Unique need for temporary storage of radioactive waste after major incidents.* As recognized in response to the Fukushima Dai-ichi NPP accident, significant thought and planning should be directed towards the siting and usage of temporary waste storage areas across the affected region. These storage areas have also been referred to as staging areas. The large demand for numerous temporary storage facilities is a unique need following large-scale radiological and nuclear incidents. A key feature of these sites should be ease of retrieval of the waste for movement to interim storage areas (smaller in number than temporary storage areas) or for permanent disposal, recognizing that handling and transport of waste should be minimized when possible.

Establishing temporary and interim storage areas is technically challenging but critical to implementing a successful waste management strategy. IAEA teams assisting the Government of Japan during the Fukushima Dai-ichi NPP recovery response listed the following necessary items for managing waste (IAEA, 2011a):

- infrastructure for managing very large volumes of generated material (including collection and segregation by activity level at the source);
- establishment of numerous temporary storage facilities, transportation systems, volume reduction treatments, and municipal landfills with sufficient capacity to accept disposal of unconditionally or conditionally cleared material;
- determination of site locations for interim storage facilities for large volumes that meet the timeframe for storage; and
- establishment of designated final disposal locations for different types of waste.

It is recommended that specific guidance on siting, construction, operation, monitoring, disassembling and documenting of temporary radiological waste storage areas be developed by the appropriate level(s) of government as soon as practicable after the commencement of response activities. In fact, development of such guidance even before an incident has occurred will be extremely advantageous. For example, lessons learned from the Chernobyl nuclear reactor accident indicate that the temporary storage sites constructed shortly after the accident were established without hydrogeological investigations, engineered barriers, or any design documentation. Many of the temporary facilities, estimated to be about 800 trench facilities alone, are out of regulatory control because of the difficulty of locating over 50 % of the inventories of these facilities even 25 y after the disaster (IAEA, 2011a).

4.2.2.2.3 *Considerations for management of radioactive waste generated from materials outside of Atomic Energy Act processes and activities*. In responding to a radiological terrorism incident such as an RDD or IND, planners and decision makers may need to identify conditions under which different waste disposal options would be considered. Because such an incident may generate very large volumes of waste, consisting of different waste types and different levels of hazard, it may be advisable to evaluate available disposal options to determine whether they can provide the necessary disposal capacity with adequate protection for human health and the environment. Such decisions will need to be made within the statutory and regulatory framework under which the response is being conducted and integrated with the other policy decisions guiding the effort. For example, a key decision will be whether to apply a strict interpretation of the definition of LLRW to all incident-related waste as a default position. This uncertainty arises because the current definition of LLRW is a definition by exclusion (*i.e.*, not spent nuclear fuel and not high-level radioactive waste) and the circumstances of the terrorism incident and the radioactive materials involved would likely be outside the statutory/regulatory scheme set forth for processes and activities conducted under the Atomic Energy Act (AEA, 1954). It would be prudent for decision makers and authorities responding to a radiological terrorism incident to gain legal guidance from appropriate sources (federal, state and/or local government and others as appropriate given the site-specific factors) before designating waste as low-level radioactive waste under 10 CFR Part 61 (NRC, 2013a). Decision makers should ascertain, with legal advisors at the time, whether a traditional LLRW paradigm is warranted or whether an alternative risk-informed approach to waste disposal is more appropriate and can provide the necessary level of protection.

Additionally, it is not clear if the legal complexities around proper radioactive waste designation and/or definition would be further complicated, and the available disposal options possibly more constrained, if the radioactive source used in the terrorist device were a NRC/Agreement State licensed source, or material diverted from a U.S. Department of Energy (DOE) site instead of being a terrorist-deployed radioactive source that is unlicensed or of foreign origin.

Waste handling and disposal considerations will be difficult and are likely to involve many stakeholders. These considerations are discussed in detail in Appendix B and also in Section 5. Updating the existing radioactive waste policy, such as developing a national risk-based waste classification as recommended by NCRP (2002a), would help alleviate the problem, as would granting flexibility to the current regulatory system to address the aforementioned issues on managing radioactive waste (Section 5.6.1).

4.2.2.3 *Management of Commodities and Drinking Water.* Following contamination of the affected area, there could be issues raised about the commodities (such as agricultural products) that are locally produced regarding their suitability for local consumption or for sales or exports to areas outside the affected region. It is important that careful attention be paid to standards for export and import of the commodities, such as the Codex Alimentarius Commission (Codex, 2012) for food exports, and Customs and Border

Patrol guidelines for imported goods (Section 6). The concern will likewise apply to the drinking water drawn from contaminated water bodies. Depending on the nature of the region affected by the release (*e.g.*, urban, rural, industrial, agricultural), there is the potential for a wide variety of commodities to be affected. These could range from food and water to consumer products and raw materials. There are likely to be issues of widespread surface contamination as well as the possibility of incorporation into products, particularly for long-lived radionuclides. A long-term monitoring program will be needed to evaluate the extent of contamination and inform decisions about the safety of introducing such products into commerce. In some cases, monitoring may be needed to support regulatory action to prevent the distribution of contaminated products.

The management of surface-contaminated commodities may be relatively straightforward and simple decontamination techniques may be sufficient to allow consumption of the product. However, especially in the case of food, testing will be needed to confirm that levels are below the prevailing guidelines. Likewise with drinking water, there may be methods to remove contamination to prescribed levels, but this will need to be confirmed by sampling and testing. The Fukushima Dai-ichi NPP accident demonstrated the need for release criteria for many other classes of products not previously considered.

In considering the future production of commodities, the primary concern would be introducing long-lived radionuclides into raw materials that might be incorporated into the commodities. Because water is a key component in the production of many commodities the purity of the water supply is an important factor for processed foods and pharmaceuticals, especially biological products. Manufacturers will need to consider their whole supply chain to ensure that radioactive materials have not entered their products. In the past, there have been incidents where radioactive material was transferred to foundries, resulting in contaminated steel that was used in consumer products. The need for monitoring may continue well into the future. Section 5.5 addresses options for recovery and Section 6 examines long-term monitoring in further detail.

4.2.3 *Long-Term Issues and Management Considerations*

Depending on the magnitude of an incident, there could be a need to conduct long-term follow-up monitoring of the affected populations, commodities, and environment after the cleanup of contaminated areas and the restoration of the community. Long-term monitoring may include the following:

- health effects (including physical and psychological effects);
- environmental contamination and impacts; and
- contamination of locally produced food, crops, and drinking water.

Depending on the incident scenario and site-specific conditions, it may be necessary to consider long-term monitoring of any continued exposure to residual contamination. This need is particularly important when contamination is extensive and widespread. Decisions involving these issues would include the extent and effectiveness of such monitoring efforts, as well as the ultimate determination of cessation of such actions.

4.3 Site-Specific Optimization Framework in Decision Making

This section discusses the optimization framework for the late-phase recovery process to addressing the aforementioned issues, in light of existing guidance. The actual implementation of the process is described in Section 5.

4.3.1 *Basis of Decision Making*

Because of the extremely broad range of issues and potential impacts that would occur from an RDD, IND, or major NPP accident, traditional approaches to environmental decision making may not be suitable for recovery from such incidents.

Many of the issues are interconnected, requiring a multi-faceted approach to return the community to normality. For illustration, consider the simple example of using facility workers to restore a critical industrial facility. Although the workers might be provided transportation to the facility, they would also have other basic needs including shelter, food, family services, laundry facilities, and schools for children. To have a productive workforce, the needs of the worker's whole way of life should be addressed.

While most traditional cleanup approaches focus primarily on the individuals' and the community's potential long-term health risks with predetermined criteria, the complex nature of the incidents in question will compel decision makers to weigh all available resources at hand against the potential risks and set priorities for a timely recovery. The approach to address wide-area contamination necessarily departs from traditional practices because additional parameters and considerations affect the overall decision making. As stated by DHS (2008a), using "a pre-established numerical cleanup guideline is not recommended as best serving the needs of decision makers in the late phase."

Decision making involves societal choices about how much the new conditions will differ from those before the incident, and there is no simple approach to making these decisions. Rather, a process is needed that systematically incorporates the important elements to reach an agreement under a multitude of constraints. This process involves consensus-building to reach that agreement, with the goal of optimizing the benefits for all involved.

The ideal process will be an integration of decision making with the expressed values of society. There must be a realization that individuals do not make choices solely on the basis of risk or cost, and there is a gradient of tolerance for risk (*e.g.*, unacceptable, tolerable, acceptable, negligible) and willingness to accept cost across society. Consensus decision making involves determining what is acceptable to most people in the conditions that are able to be obtained in the near and distant futures. A balance between present and future consequences must be reached. Cumulative impacts must be considered and a complex set of risks (not just limited to radiological risk) must be evaluated. A diverse population must also be considered with a range of susceptibility to various risks. Consequently it is important to look across disciplinary boundaries and examine processes that could be used to facilitate decision making.

4.3.2 *Principle of Optimization*

Incident- and site-specific optimization for late-phase recovery is a multifaceted approach aimed toward resolving a complex situation with the goal of achieving a state of physical, mental and social well-being for the affected population.

The term *optimization* is used by professional organizations and government agencies to describe the process of systematically incorporating objectives and constraints to resolve a complex situation while addressing what is important to stakeholders.

The principle of optimization has been a key principle in radiation protection for many decades. It has been recommended by international and national regulatory and advisory bodies including ICRP (2007) and NCRP (1993; 2004). The latest international guidance from ICRP Publication 103 (ICRP, 2007) defines optimization as follows:

> "The principle of optimisation is defined by the Commission as the source related process to keep the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual

> doses as low as reasonably achievable, taking economic and societal factors into account" [also referred to in the United States as the ALARA principle (NCRP, 1993; 2004)].

The process of optimization of protection is intended for application to those situations that have been deemed to be justified, and the principle of optimization with restriction on the magnitude of individual dose or risk, is central to the system of protection. ICRP Publication 111 (ICRP, 2009) provides further guidance for protection of people who live in an existing exposure situation such as is the case in late-phase recovery following a nuclear or radiological incident.

Incident- and site-specific optimization for late-phase recovery following a large radiological incident is a multifaceted approach to resolving a complex situation with the primary goal to establish societal objectives that include possible future land uses, cleanup options and approaches, technical feasibility, costs, cost-effectiveness, infrastructures, local economy, and public acceptance. Using site-specific optimization helps ensure that the affected population can achieve a state of complete physical, mental and social well-being. For a small-scale attack (such as one confined within a city block) an expedited cleanup effort (using a simple, predetermined approach) is likely, while an incident causing extensive contamination (*e.g.*, affecting tens of city blocks in a major urban area or more) will require considerable effort to reach decisions on final cleanup criteria and technology used. It is important to note that optimization and justification are interrelated principals of radiation protection, and optimization should always be done within the context of justification. That is, all exposures and the degree of exposure must be justified.

The major approaches of the optimization process include:

- *Aim to achieve the ALARA principle*: Used both in concept and as a regulatory requirement for the control of radiation in nuclear and radiological facilities. It has been included in regulation and guidance from both national and international regulatory and advisory bodies. The optimization process is built around the idea of adhering to the ALARA principle.
- *Integrate stakeholders in decision making*: Because of the multitude of economic and societal factors required to achieve the ALARA principle and return people to an affected area, critical input is needed from stakeholders of various sectors. The involvement of the wider community can build trust and credibility. The decisions made through discussions with a

wide range of individuals will improve the buy-in from various sectors of the community, leading to improved sustainability of the final decisions (Section 5.6.2).

- *Maintain flexibility*: Due to the rarity of nuclear or radiological attacks and major NPP accidents, society is generally unfamiliar and unprepared to cope with such incidents. As a result, the routine practices and procedures that are commonly used in daily life may not be conducive to developing an expedient approach to the late-phase recovery effort. The need to maintain flexibility to streamline response operations in order to expedite the recovery process has been reflected in lessons learned from major incidents (Appendix A).
- *Use a scaled approach*: Emphasizes that efforts devoted to risk management should be proportional to the underlying risks and is recommended by the Presidential/Congressional Commission on Risk Assessment and Risk Management for environmental health risk management (Omenn *et al.*, 1997a; 1997b). The scaled approach is also consistent with the ALARA principle and is directly applicable to the highly varied situations that are both incident and site specific.

4.3.3 *Optimization Process*

The risk management principles used in long-term recovery were elaborated in the report mentioned above that was released in 1997 by the Presidential Commission on Risk Assessment and Risk Management (Omenn *et al.*, 1997a; 1997b). The Commission described an iterative process of engaging stakeholders in managing risk throughout the decision-making process. Building on this iterative process, a new process using the optimization approach was developed specifically to address nuclear and radiological issues and health risks, economic issues, societal impacts, and environmental impacts in the short and long term (including waste generation). This iterative approach involves seven distinct steps including:

1. define situation;
2. assess impacts;
3. identify goals and options;
4. evaluate options;
5. make decisions;
6. implement decisions; and
7. monitor and evaluate.

As the recovery requires a process that is focused on the community, the optimization approach is one that is necessarily incident and site specific. To this end, every key decision must be centered on the stakeholders as depicted in Figure 4.2, with additional details described in Section 5. The iterative nature allows for changes as new information is developed during the late-phase recovery.

4.3.4 *Guidance on Optimization*

4.3.4.1 *Principle of Optimization*. As noted in Section 4.3.2, radiation protection principles have been prescribed by ICRP and NCRP. These principles include: justification of protection, optimization of protection, and restricting exposure to individuals. Although the protection principles remain unchanged in different exposure situations, the protection strategy and applications can vary. Guidance on how to control radiation exposure by applying these principles in different situations was outlined in ICRP Publication 103 (ICRP, 2007) where exposure situations were characterized for the purpose of controlling radiation doses. Three types of exposure situations warrant radiation protection consideration:

- planned exposure situations;
- emergency exposure situations; and
- existing exposure situations.

Existing exposure situations include land contamination after a major nuclear or radiological incident. When an incident has moved from the early and intermediate phases into the late phase, the situation is considered an existing exposure situation although the time of demarcation may not always be clear.

ICRP Publication 111 (ICRP, 2009) further developed guidance on protection for existing exposure situations where the fundamental protection principles include the justification of implementing protection strategies and the optimization of the protection achieved by these strategies. The optimization process strives to ensure that there is an overall net benefit to society as well as to individuals when populations are allowed to stay in or return to contaminated areas. Dose limits do not apply because existing exposure situations cannot be managed in an *a priori* fashion (ICRP, 2009). Consequently reference levels may be considered during the optimization process to plan protection strategies that reduce residual doses below such levels.

4.3.4.2 *Long-Term Monitoring and Management*. Following a major nuclear or radiological incident, residual contamination may remain over time and require continued attention. Depending on the level of residual contamination and other societal factors, a commitment to long-term radiation surveillance and monitoring of

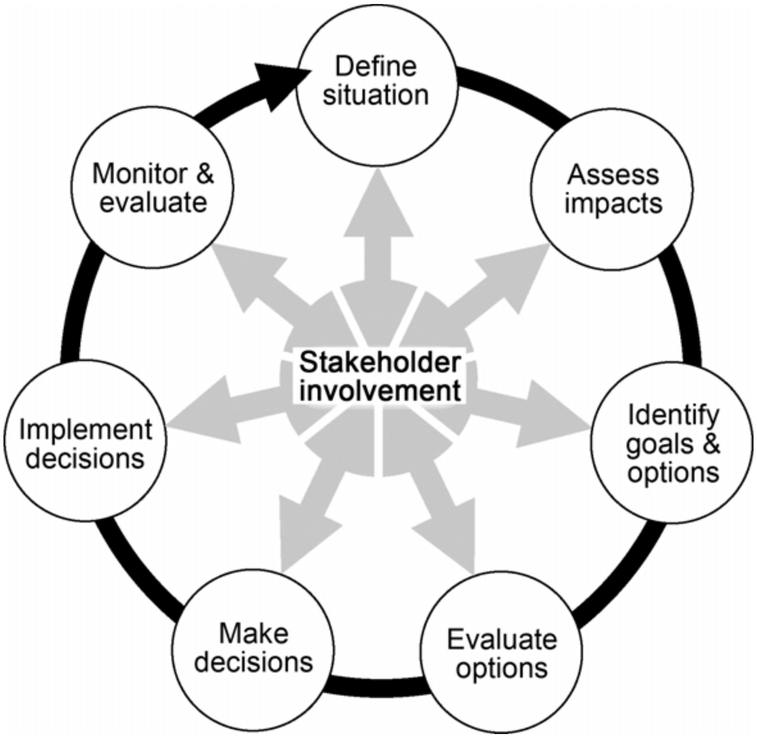

Fig. 4.2. The decision-making process for late-phase site-specific optimization approach is iterative and involves stakeholder collaboration (Omenn *et al*., 1997a).

human health and the environment long after the recovery is completed should be considered. Additional long-term protective actions and management may thus be required for contaminated natural resources and/or commodities in affected areas.

4.3.5 *Cleanup Criteria and Standards*

Cleanup criteria and standards will ultimately be developed for long-term recovery, but they need not be developed prior to taking initial cleanup actions. Decision makers and locally affected stakeholders should approach the site with a "clean slate" and derive cleanup levels through the site-specific optimization process; a unique solution to the specific problem at hand. Some general steps can be taken to clean contaminated areas to help reduce dose levels. There are also passive actions that will lessen contamination over time, such as decay of radionuclides and weathering. Cleanup actions should be considered iteratively with ongoing monitoring and stakeholder consultation. The cleanup will continue until stakeholders find the monitored dose levels acceptable, meeting the established cleanup criteria set by a process involving local government, federal agencies, and all other stakeholders affected by the incident.

4.4 Steps Toward Long-Term Recovery

> Preparedness initiatives will help guide the recovery process in achieving the community's recovery objectives in an effective and efficient manner.

4.4.1 *Recovery Planning*

Proper pre- and post-incident planning is required for a well-coordinated recovery process at all levels of government. The preparedness initiatives will help guide the recovery process in achieving the community's recovery objectives in an effective and efficient manner. Both pre- and post-incident planning activities will contribute to the resilience and timely recovery of the community.

4.4.1.1 *Pre-incident Recovery Planning*. Planning activities are intended to strengthen community resilience. The pre-incident plan provides a common platform for all parties involved in recovery decisions and activities and is integrated with local and regional community development. The planning effort helps identify priorities and incorporates hazard mitigation strategies as well as post-incident options. During the pre-incident planning, it is important to establish clear leadership roles, coordination and decision-making structures and hierarchy at all levels of government. In addition, strong partnerships are developed to engage all potential resources and actions are taken to develop and implement recovery training and education.

Several important elements for pre-incident recovery planning activities include (FEMA, 2011b):

- *Performing assessment*: Includes identifying hazards, assessing risks and vulnerabilities, and identifying limitations, resources and challenges.
- *Conducting communication and outreach*: Develops strategies to engage stakeholders and ensure community participation and develops communication approaches in the post-incident recovery.

- *Involving stakeholders*: Identifies sectors of the community to participate in pre- and post-incident recovery planning and coordination.
- *Developing partnerships*: Develops pre-incident partnerships that ensure engagement of all potential resources and connection with public and recovery partners and stakeholders.
- *Developing guiding principles and recovery priorities*: Develops guiding principles for recovery decision making and for setting priorities, and incorporates overall sustainability into the planning guidance.
- *Establishing organizational framework*: Establishes clear leadership, coordination and decision-making structures and hierarchy throughout all levels of government.
- *Establishing concept of operations*: Develops the operational framework and procedures to implement the post-incident plans.
- *Explaining the process for post-incident recovery planning*: Develops a process for conducting the post-incident planning, which defines the responsibilities and functions required to manage the likely conditions and needs after an incident.
- *Conducting exercises*: Tests the pre-incident planning, preparedness and capabilities by implementing recovery exercises, and also evaluates the performance and makes improvements from lessons learned.
- *Establishing baseline radiation levels*: Characterizes background radiation levels prior to any incident in order to place into perspective measurements made afterwards and to provide information to assess the impact and magnitude of the additional radiation exposures.
- *Identifying planning considerations*: Incorporates site- or area-specific considerations into the planning process, which may include: wild/rural/urban interfaces, floodplain management, coastal zones, seismic areas, and historical and cultural factors.

Engaging stakeholders in decision making is critical to a successful recovery effort. As people learn, they gain a deeper understanding of the risks and trade-offs that are available as options. Stakeholders and all responsible parties must be willing to negotiate and be flexible. This is particularly true in a society that is likely to find itself under severe resource and time constraints when a major incident occurs. Such limitations tend to impose serious challenges to all parties seeking viable solutions that could be both acceptable to stakeholders and possible to implement by responsible parties.

Guidance has been provided by NA/NRC (2006; 2009), the Congressionally-mandated Commission on Risk Assessment and Risk Management (Omenn *et al.*, 1997a; 1997b), and NCRP (2004). For stakeholder engagement specifically in radiation protection issues, HPS (2010) and IRPA (2009) have published the following guiding principles:

- identify opportunities for engagement and ensure the level of engagement is proportionate to the nature of the radiation protection issues and their context;
- initiate the process as early as possible, and develop a sustainable implementation plan;
- enable an open, inclusive and transparent stakeholder engagement;
- seek out and involve relevant stakeholders and experts;
- ensure that the roles and responsibilities of all participants, and the rules for cooperation are clearly defined;
- collectively develop objectives for the stakeholder engagement, based on a shared understanding of issues and boundaries;
- develop a culture that values a shared language and understanding, and favors collective learning;
- respect and value the expression of different perspectives; and
- ensure that a regular feedback mechanism is in place to inform and improve current and future stakeholder engagements.

These guiding principles provide sound counsel to radiation protection professionals for successfully engaging stakeholders in decision making that result in mutually agreeable and sustainable decisions.

4.4.1.2 *Post-Incident Recovery Planning*. In certain aspects, post-incident recovery planning activities mirror that of the preplanning effort, except that the post-incident planning should take into account the reality and specificity of circumstances that follow an incident that are unknown beforehand. The key principles for post-incident recovery planning are shown in Figure 4.3. The communities affected by an incident should develop a process for optimally managing their recovery effort and resources. The planning process provides the benchmark to measure the affected communities' progress toward a successful recovery.

Post-incident recovery planning includes reassessing the strategies established during the pre-incident planning by integrating

Key Principles of Post-Disaster Recovery Planning

All disaster-impacted communities can benefit by engaging in disaster recovery planning and creating plans that are meaningful to multiple audiences, including potential funders. Tribal governments, state and federal level agencies, an members of the community. The post-disaster planning process:

- Organizes recovery priorities and tasks through the use of a planning process to:
  - evaluate the conditions and needs after a disaster;
  - assess risk;
  - set goals;
  - identify opportunities to build in future resilience through mitigation; and
  - identify specific projects in areas of critical importance to the community's overall recovery.
- Uses a community-driven and locally managed process, designed to promote local decision making and ownership of the recovery planning and implementation effort.
- Works collaboratively with all groups of people affected by the disaster to promote inclusive and accessible outreach to their communities and address issues relevant to them. Ensures inclusion and encourages participation of individuals and communities that may require alternative and/or additional outreach support (*e.g.*, racial/ethnic communities, individuals with limited English proficiency, and people with disabilities).
- Incorporates considerations that include the concept of "growing smarter" as the recovery continuum progresses. This includes compliance with standards for sustainable and accessible design, alteration and construction.
- Integrates multihazard considerations into mitigation and preparedness activities.
- Builds partnerships among local agencies, jurisdictions and state, tribal and federal governments.
- Provides well-defined activities and outcomes—including schedules and milestones—aimed at achieving recovery.
- Develops tools and metrics for evaluating progress against set goals, objectives and milestones.
- Identifies resource requirements and conducts acquisition planning.

Fig. 4.3. Key principles of post-disaster recovery planning (FEMA, 2011a).

the information obtained during the post-incident planning. All these activities should incorporate the newly obtained data with implementation in mind, including securing the funding sources for the recovery effort. In addition, since the recovery effort will likely be an iterative process, a flexible mechanism should be developed to adapt the approach to any changing situations.

4.4.2 *Remediation of Contamination*

The issues specific to radiological aspects involving an RDD, IND, or major nuclear reactor accident involving widespread contamination should be addressed in both pre- and post-incident planning activities discussed above. In general, remediation of radioactive-contaminated areas in the late-phase recovery stage would be no different from that which has been practiced in the statutory cleanup activities discussed in Section 4.2.2.2 (more in-depth technical approaches are described in Section 5). The key elements for such actions include the following:

- characterize contamination;
- conduct risk assessment;
- evaluate feasibility (including technology and costs);
- perform cleanup activities;
- address ancillary issues including waste management; and
- assess results and document lessons learned.

It should be noted, however, that remediation for incident-related contamination, especially when the contamination is widely spread, could present special difficulties. Because large-scale radiological incidents are rare and information needed for risk assessment would be incident and site specific, performing risk assessment requires a comprehensive characterization of radioactive contamination and its subsequent movement in the environment. Although much experience and knowledge have been gained over the past few decades from cleanup activities conducted under various statutory requirements [including the EPA Comprehensive Environmental Response, Compensation, and Liability Act (also know as Superfund) (CERCLA, 1980) cleanup activity, the DOE effort to remediate its former nuclear weapons complex, and the NRC effort to decommission its licensed facilities], their direct applicability to incident-originated situations is not entirely clear, specifically for RDD, IND terrorist attacks, and major NPP accidents. Thus, additional information gathering and optimization efforts would be warranted for situations pertaining to these major nuclear or radiological incidents (Chen and Tenforde, 2010).[3]

[3] Nisbet, A. and Chen, S. (2013). "Decision making for late-phase recovery from nuclear or radiological incidents: New guidance from NCRP," presented at the ICRP 2013 Commission Meeting in Abu Dhabi (Illinois Institute of Technology, Chicago).

5. Implementation of the Optimization Framework for Decision Making

5.1 Role of Optimization in the Decision-Making Process

The recovery process comprises a sequence of interdependent and often concurrent activities that progressively advance a community toward normality. Consequently, the recovery effort requires a well structured organization that can optimize decision making.

This section describes how the optimization process can be applied to a large-scale radioactive contamination incident to make decisions for the return of members of the public and who will be involved in making those decisions. The key steps in decision making were shown in Figure 4.2. These steps are designed to be applied on a site-specific basis at multiple geographical scales (*i.e.*, local, county, state and region). Multiple teams of individuals will be tasked with applying the steps within their region, with active stakeholder involvement at every step. It should be noted that much of the information discussed here was drawn from the experiences and lessons learned from major nuclear and radiological incidents described in Appendix A.

5.1.1 *Role of Optimization in the Decision-Making Process*

The recovery effort requires a well-structured organization with clear roles and responsibilities and closely-coordinated functions to implement the optimization framework outlined in Section 4.3.

NDRF (FEMA, 2011b) describes the recovery process as a sequence of interdependent and often concurrent activities that progressively advance a community toward a successful return to normality. Figure 5.1 depicts a hypothetical organizational approach. There may be several technical working groups which focus on different segments of the contaminated area (*i.e.*, Areas A, B, C, and D in Figure 5.1) and bring their recommendations to a common recovery-management team, who coordinate input from the stakeholder working group. Final decisions are made by the decision team. The

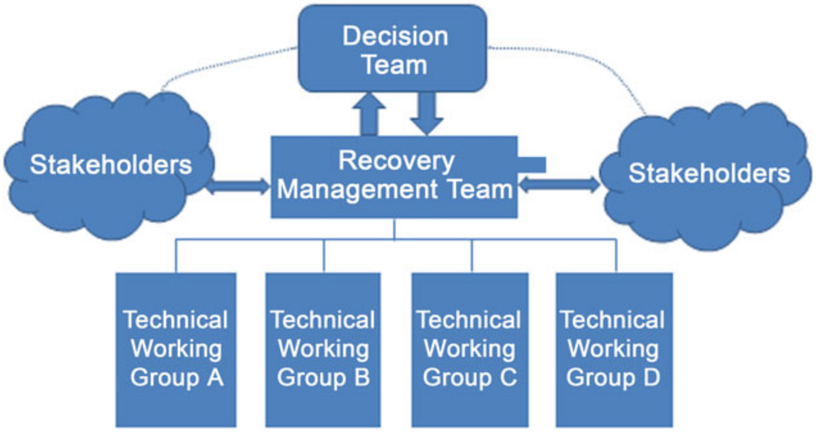

Fig. 5.1. An organizational approach for the recovery process that assigns clear responsibilities for a sequence of interdependent and often concurrent activities that progressively advance a community toward a successful return to normality.

stakeholder working group is depicted as connected to the decision team, rather than within an organizational box. As described in Section 5.1.1.4, the stakeholder working group comprises many individuals of diverse interests and talents, with different individuals for different geographic areas addressing different issues, and frequent turnover in the particular individuals who are working on various issues. Additionally, while the formal working relationship may be between the stakeholder working group and the recovery-management team, stakeholders may often wish to present certain issues directly to the decision team, so a dotted line was drawn in Figure 5.1 to depict this informal working relationship.

5.1.1.1 *Decision Team*. The decision team consists of the federal government (*e.g.*, cabinet level officials), state government (*i.e.*, the governor), local government (*i.e.*, the mayor or equivalent), and representatives of other supporting federal agencies. This structure encourages active participation at the local level (mayors) with the understanding that decisions will need to consider a wider approach that is balanced across the region.

While a key consideration for the decision team is to use the best available science, it is recognized that decisions may have to be made amid considerable scientific uncertainty. The decision team will have to manage the economic restraints placed on solutions and consider the economic consequences of various risk management scenarios. The decision team will also be bound by legal and institutional restraints, unless waived or otherwise altered. Finally, the decision team will be the ultimate arbitrator of possibly conflicting public values, such as equity and sustainability. They are generally elected officials who serve the people's interest.

Other members of a decision team at the state level may include: the attorney general; the commissioners of the departments of health, environmental protection, community affairs and agriculture; and the superintendent of the state police, all assisted by staff from their agencies to provide support for the recovery effort.

5.1.1.2 *Recovery-Management Team*. The recovery-management team consists primarily of the government sector (cabinet level officials), affected state or local officials, and the federal lead technical agencies. This team is responsible for coordinating and managing the recovery activities. It also coordinates the efforts of the stakeholder and technical working groups, providing advice and recommendations to the decision team based on the input and analyses of the working groups in the following areas:

- collecting, analyzing and presenting data;
- conducting technical analyses;
- presenting risk comparisons; and
- identifying risk reduction opportunities.

The recovery-management team should draw on the expertise and structure of the state and county offices of emergency management to ensure site-specific issues are considered.

The recovery-management team should also be the repository of all collected data, and the data should be carefully described and maintained in accord with a data-management plan. The data quality and associated uncertainties could change over time, so it is important to ensure that these aspects of the data are also collected and archived with the data themselves (IAEA/NEWF, 2011).

Although contaminant concentrations are the most likely measurements readily available from various locations, it is important to ensure that decisions about dose and risk reduction also consider the potential or likelihood of exposure. There may be areas (*e.g.*, forest, open space, recreational areas) that represent a low potential for public exposure. Risk reduction activities should concentrate on reducing dose and mitigating risk to members of the public, rather than on reducing concentrations of radionuclides in environmental areas with limited public occupancy. Prioritizing decontamination efforts for areas where public exposure is likely is an important optimization technique.

5.1.1.3 *Technical Working Group*. One or more technical working groups should be formed and convened shortly after a major nuclear or radiological incident. The technical working group should be managed by the planning unit of the incident command, recognizing that the initial focus will be on the early-phase activities such as rescue and triage.

The function of a technical working group is to provide multiagency, multidisciplinary technical and analytical support to the planning unit to assist them in the optimization process. These technical issues may include: analyses of regulatory guidelines and requirements, risk analyses, options development, and cost-benefit analyses. The role of this group is strictly advisory in order to ensure objectivity throughout the process; it makes recommendations, not decisions.

A technical working group consists of both government and private-sector representatives, with subject matter expertise to address various technical aspects of the recovery process. It conducts or manages the optimization analyses in the following specialty areas (DHS, 2008a):

- environmental fate and transport modeling;
- risk analysis;
- technical remediation options analysis;
- cost-risk-benefit analysis;
- health physics/radiation protection;
- regulatory requirements;
- sociopolitical issues;
- public communication of technical information; and
- consideration of psychosocial issues.

The selection of the technical working group membership and expertise, as well its depth and breadth of the coverage will be incident specific. A shared responsibility of all the members is to assess the technical information available, and plan the long-term recovery operations. Each discipline will bring its own expertise, but the final product will be a blending of all of the expertise, with shared responsibility and ownership of the recovery plan.

Professional communicators, rather than technical professionals should speak with members of the public and press. Professional risk communicators can help to contextualize messages about risk and exposure beyond the purely technical considerations.

5.1.1.4 *Stakeholder Working Group*. The stakeholder working group provides critical input to the decision team. This group consists of government sector (federal, state and local) representatives, community groups, representatives of different cultural or ethnic groups, local business interests, labor unions, environmental advocacy groups, consumer rights organizations, faith-based organizations, educational or research institutions, trade associations, and members of the public. It provides advice on the attributes of the community and how they should be valued or weighted during the optimization analyses. It also provides review and input for the technical working group on land use and community needs.

The stakeholder engagement process begins by identifying potential stakeholders. Stakeholders could include people who might be affected by the risk management decisions (those with homes/schools/businesses/farms in the affected areas) as well as people who may be affected but as yet are not aware of it (*i.e.*, those who visit the area, obtain goods or services from the affected area, or those who live in an area that is under consideration for accepting waste from the affected area). Other stakeholders are those who may have information and expertise that could be helpful (*e.g.*, nongovernment organizations with radiation expertise, but who are from outside the affected area), or those who might have been involved with similar risk management situations in another location. Stakeholders may simply be people who have expressed interest in being involved, or who might reasonably be angered if they are not included. Stakeholder involvement efforts should attempt to engage all potentially-affected parties, and solicit a diversity of perspectives.

It can be challenging to include diverse and vulnerable populations in stakeholder processes. Officials must consider different cultures within the community (with appropriate interpreters available), and vulnerable populations such as the disabled, children, elderly and homeless. Emergency planners who seek to involve stakeholders from diverse populations may consider partnering with community and faith-based organizations that already work with the people and are viewed as trusted sources of information. Working with the ethnic media can help amplify the community messages and reach people who may have limited English language skills.

It is essential in working with stakeholders that government representatives do not attempt to tell people what to do, but rather listen to and work with the stakeholders. The main concerns could be simple subsistence issues, such as putting food on the table and buying shoes for their children. If they are asked to consider the risk of radiation on top of their more pressing concerns, they could find the whole picture too overwhelming. It is important to start a conversation, and bring up what actions could potentially reduce radiation exposure, and how simple actions may be helpful in protecting children and the elderly (Pittman, 2011).

While there may be an initial reliance on formal stakeholder meetings, a communication plan should include regular meetings with affected people in smaller groups. This can be an opportunity to hear directly what their priorities are, and to provide them with tools that best fit their lifestyles and help them to manage their radiation exposure.

5.1.2 *Evaluating Societal Needs*

> To achieve societal acceptance of the sustainable conditions after a major nuclear or radiological incident, recovery decisions must be made in concert with societal values.

It is possible to prioritize resources based on a risk assessment/risk management paradigm, modeling exposures, and presenting risk trade-offs in relation to costs. However, to achieve societal acceptance of the sustainable conditions after a major nuclear or radiological incident, recovery decisions must be made in concert with societal values. The stakeholder working group provides the mechanism to elicit the values that the affected population deems important.

When setting goals, there are minimum requirements (must haves) as well as wants and desires (Baker *et al.*, 2001). Stakeholders need to be able to express their desired outcomes as part of the decision-making process.

The long-term nature of the recovery process adds an additional level of complexity. Many of the solutions will continue long into the future, and the costs of those solutions will also continue. Several important questions should be considered such as:

- What mechanisms allow decision makers to balance the present and future consequences of decisions?
- How are cumulative impacts, synergisms, and diverse populations accounted for?
- How important are considerations for future generations?

Conversations with the stakeholders will be necessary to develop an acceptable discount rate with which future costs and benefits will be adjusted. These are “questions of distributive justice, as the choice places an implicit value on the health of future local residents” (NCRP, 2004).

Of all of the risks affecting the population, which do the stakeholders consider to be the most significant? It is important that the affected population be provided with clear information on the risks, costs and benefits of the various options under consideration. As discussed in NCRP Report No. 146 (NCRP, 2004), when presented with “clear and sufficient information,” communities are able to choose between appropriate options. The same report states “case studies showed that communities were able to accept some risk if explicit public involvement and input were sought and incorporated into risk management decision making” (NCRP, 2004). The key role of the stakeholder working group is to determine what risks the community is, and is not, willing to accept. Some risks may be unacceptable but others may be tolerable or even deemed negligible (Lochard and Pretre, 1995).

When addressing mitigation of the risks facing the population, the decision making about which protection options to select must include some questions about practicality (*e.g.*, economics, available and demonstrated technology, politically acceptable to the stakeholders), and equitable allocation of the costs and benefits associated with risk reduction. It is important to consider distributional impacts of various alternatives, and that all involved discuss what they perceive to be “fair.” Different groups may have different ideas of what is fair, and those notions must be openly discussed. NCRP Report No. 146 points out that historically, “radiation protection guidelines have focused on distributive fairness” while “applying principles of utilitarian justice to balance the societal costs and benefits of reducing population risk” (NCRP, 2004). Thus, different definitions of fair may be used in different parts of the decision-making process.

Obviously, there will be competing goals. Part of the optimization process is to clarify those goals and allow different groups to advocate for those goals. Integrating these considerations will be a key role for the decision team.

5.1.3 *Acceptance of Decisions*

Any major decision regarding recovery needs to engage the stakeholders closely because no matter how valid a cleanup option may be, or how sound the science is, if the option is not accepted, it will fail. Thus, developing a comprehensive and effective scheme for involving stakeholders in decision making is essential to achieve the recovery objective. Toward this end, considerations should include issues that are specific to local and regional needs, cultural and ethnic cognizance, special needs, justice, and equity. Thus integration of the stakeholders into the decision-making process, development of effective communication methods and the ability to accommodate feedback from stakeholders in a timely fashion is essential to the process.

Stakeholder acceptance requires that a level of trust be established regarding the validity of the information about the cleanup options that are communicated. This trust has to be earned, it is not automatic, and society no longer accepts "expert" information uncritically. This is particular true for radiological issues due to pre-existing public concerns. Trust comes from building credibility and respect with the stakeholders through the use of sound science, transparency in the methods and decisions, and responsiveness. It also comes from the way information and decisions are communicated. For this reason, special emphasis needs to be given to the tools and methods used to communicate the information.

It is important for decision makers to recognize that not *all* the answers will be known. For example, it may not be known what all the important inputs are for identifying the exposure pathways of potential concern. Experience will guide identification of the majority of important inputs, but site-specific details may not be well-known (*e.g.*, physical characteristics, cultural practices). Thus, local knowledge and stakeholder input to the decision-making process will result in a better evaluation of the situation. Furthermore, seeking, valuing, and publicly acknowledging stakeholder input of this type will help to foster trust and credibility.

Similarly, there will be differences in how individual stakeholders will prioritize the variety of factors that could be considered in the decision-making process (Section 5.3.2). It is likely that many stakeholders will assign different priorities to any given set of factors than do technical consultants, and that these priorities may change over time. Consequently, the system needs to be sufficiently flexible that it can accommodate the changes in stakeholder opinion that will inevitably occur as the recovery effort evolves over time. It is also important to recognize that there may not be a single correct answer.

Careful thought needs to be given to the treatment of uncertainties in the decision-making process. For communicating results to stakeholders, emphasis is best placed on the uncertainties that influence potential decisions as opposed to uncertainties of a statistical nature that do not directly affect the decisions.

Finally, it is important to recognize that stakeholders affected by a wide-area nuclear or radiological incident are generally not a single, homogeneous group. They may represent many groups over a cross section of the society with diverse backgrounds and differing perspectives. Thus, although they may share a common long-term goal for recovery, their individual short-term interests may be conflicting and could result in a very challenging decision-making process (*e.g.*, on such decisions as radioactive waste disposal or cleanup priority), requiring exceptional efforts in reaching out to stakeholders. The effective coordination of these groups will be an important element in achieving common agreement to avoid a protracted decision-making process.

5.2 Defining Post Incident Conditions

Defining post-incident conditions includes: characterizing the radioactive contamination, describing the population demographics, evaluating the economic conditions, assessing the essential services, and appraising the psychological state of the affected population.

To achieve a successful recovery following a major nuclear or radiological incident that caused widespread radioactive contamination, the nature and extent of the impact should be defined and presented in an understandable manner to the working groups (Figure 5.1). The most obvious need is to characterize the radioactive contamination, its composition, characteristics, and spatial distribution. However, other important aspects need to be considered including: defining the demographics of the impacted area (populations that have been evacuated or relocated and that are waiting to return to their homes and livelihood), loss of essential services and other disruptions to daily life, loss of economy, and the psychological status of the affected populations. Establishing a clear understanding of the current situation provides the framework for determining the scope of the problem and a benchmark for assessing progress during the recovery process.

5.2.1 *Characterizing Contamination*

An essential element of defining post-incident conditions is establishing an accurate and detailed characterization of the radioactive contamination. This includes identifying the radionuclides present; the types and energies of emitted radiations (alpha particles, beta particles, and gamma rays); the locations of primary and secondary sources; the physical characteristics (*e.g.*, particle size and solubility); and the spatial extent, heterogeneity and mobility of the contamination. Identifying hot spots, and differentiating between mobile versus fixed contamination is essential not just for the purposes of modeling the behavior of the contamination forward in time, but also for establishing credibility with the various stakeholders in the decision-making process (Figure 4.2).

This process necessarily relies on extensive monitoring and surveillance of the contaminated areas including buildings, pavements, structures, parks, public lands, surface and ground waters, soils, and of any produce, livestock or commodities. In the case that the quality of the data available to characterize the contamination is less than desirable, this fact needs to be clearly articulated. In all situations, the most current data need to be made available, and the point in time the data represent clearly stated. This is particularly important in situations where the concentration of a radionuclide is changing relatively rapidly (as a result of radioactive decay or buildup). Consideration should also be given to defining and explaining natural background radiation levels to assist stakeholders to understand and place in perspective the contamination resulting from the incident. Ideally, the existing natural background radiation conditions would be characterized on at least a regional level prior to any major nuclear incident and thus provide a basis for understanding and interpreting contamination measurements. Remember, however, that just because contamination from an incident may be comparable to natural background levels, this fact will not necessarily make it acceptable to all or even most stakeholders.

5.2.2 *Defining the Affected Area*

One important factor to be considered is the size of the area affected by the incident. Although the impact to the local communities may not arise directly from the radiological concerns (*e.g.*, temporary shutdown of public transportation systems due to safety concerns), the extent of contamination represents a major issue in planning for recovery. Before the society can be rebuilt and the infrastructure and services restored, proper remediation of radioactive contamination to levels deemed acceptable for the reoccupation will be required. Thus, the size of the affected area will likely influence the decision on the magnitude and level of recovery. For example, a limited contamination incident (such as within a city block) might entail a relatively small effort that could be amenable to a conventional cleanup approach, whereas a wide-area contamination incident (such as tens of city blocks or more) would require substantial planning and likely involve a much more complex decision process to achieve remediation goals.

There are a variety of factors to be considered before the extent of the affected area can be defined. The physical extent of the contamination will provide the primary basis for establishing this, but other factors, such as land use and occupancy, demographics, and the availability of essential services will need to be considered. Basing the definition of the affected area on pre-existing organizational units such as municipal borders or township lines is likely to be an expedient and pragmatic approach. In a situation where there is widespread contamination, considerable care and attention will need to be given to the delineation of boundaries because of the many ramifications associated with defining a contaminated area. A balance will need to be struck between the extremes of constraining the contaminated area too tightly and thereby not providing enough safeguards to address all the requirements or desires of the stakeholders, and failing to differentiate between significant impacts and lesser impacts. For example, designating an excessively large area can result in unnecessary remediation, excessive cleanup costs, and inappropriate stigmatization of the area as unsafe.

5.2.3 *Essential Services*

One requirement for allowing evacuated persons to return to the affected area is the restoration of essential services. Essential services consist of infrastructure (such as electricity, water, sewerage, and gas or oil for heating); law enforcement (at the local, county and state levels, as well as a coordinated dispatch system); emergency services (such as fire and ambulance, as well as hospitals within range for serious illnesses or trauma); and support services (such as mail delivery, health inspections, garbage pickup, and mass transit) to ensure that those returning will be adequately protected from public health and safety issues not related to the radioactive contamination. The essential services matrix in Figure 5.2 provides an outline of these support functions.

Some critical infrastructures and services such as major highways, electrical power, water supplies, communications, transportation, healthcare, and other public services could have been damaged or disrupted by the incident, and may be on their way to being restored during the early or intermediate phases. However, some of the affected infrastructure may not be fully functional and would require continued attention. Full restoration of the infrastructure and public services is an integral component of community recovery.

Evaluating the essential services is part of the first step in framing the problem and its context. Restoration of essential services can be on a broad scale (*e.g.*, county level) or it can be done in a stepwise fashion in a municipality at a time, or even a block at a time in an urban area. The graded approach allows decision making to proceed in a step-wise fashion, always circling back in an iterative way, to help ensure that the decisions have not had unintended consequences.

5.2.4 *Identifying Land Use*

A nuclear or radiological incident that results in widespread contamination will affect a number of different lands with different uses, such as urban, residential, industrial, agricultural and recreational lands. These lands and their uses need to be identified and defined because their individual characteristics can influence the

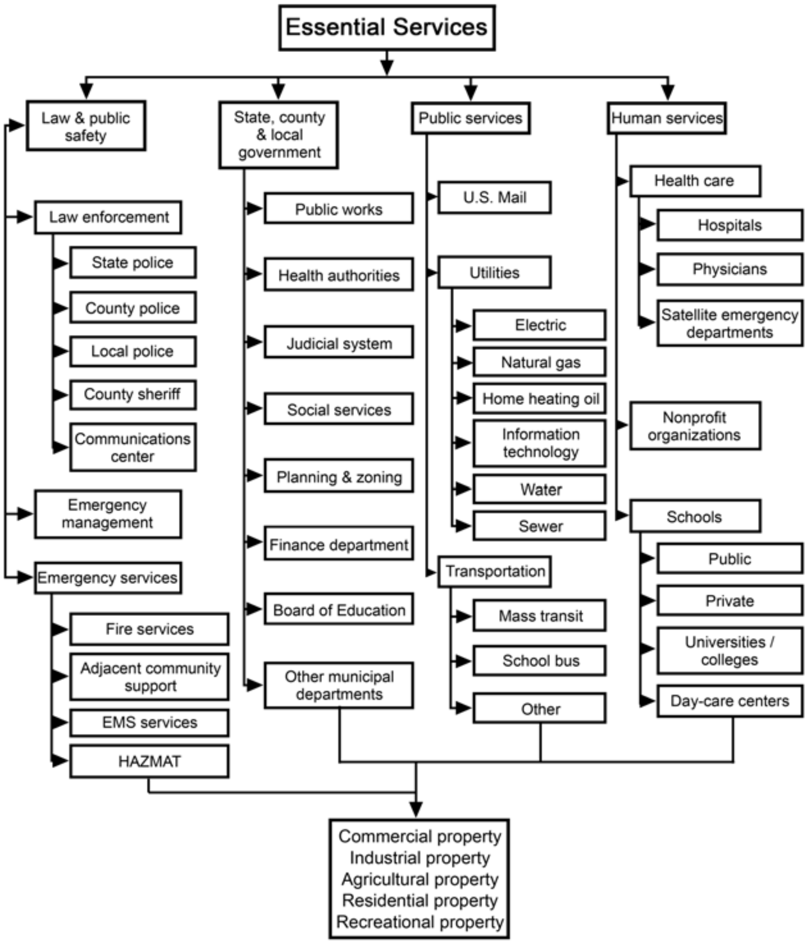

Fig. 5.2. Essential services matrix outlining the necessary infrastructure for a community on its way to recovery.[4]

movement and behavior of contamination in the environment, the potentially-relevant pathways of exposure, and the sectors of the population either directly or indirectly affected. Although many counties have land-use maps available, they may not show recent changes, such as from agricultural to residential or commercial.

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[4] Lipoti, J. (2012). Private communication to Chen, S.Y. (New Jersey Department of Environmental Protection, Trenton).

5.2.5 *Understanding Demographics*

Understanding and defining the demographics of the affected area is a prerequisite for successful recovery following a major nuclear or radiological incident. This includes the population size, and its spatial, age and ethnic distributions throughout the impacted area. Other factors to identify are the habits and activities of the population and any temporal or spatial patterns of in- or out-migration associated with the area.

Apart from allowing the characteristics of the population in the affected area to be defined, this information will be essential input to the detailed exposure assessment for characterizing the risks (Section 5.3). This allows the recovery decisions to be based on site-specific information rather than generic assumptions. Depending on the severity of the incident, some portion(s) of the population of the affected community could have been evacuated or relocated during the early or intermediate phases of the incident. The size of the displaced population imposes a certain level of urgency (such as timeliness of the cleanup effort) on the community during the recovery phase when it comes to the decision to return to the evacuated areas.

5.3 Assess Impact

Risk (the probability of adverse health effects occurring in the future) is a key factor in decision making for recovery. Experienced radiation risk assessment experts will need to evaluate exposures and potential exposures. Risk characterization should include not only the radiological hazards but also the physical, biological and chemical hazards involved.

5.3.1 *Characterizing Risks*

Risk (the probability of adverse health effects occurring in the future) is another key factor in decision making toward the late-phase recovery which may include such activities as: cleanup of contaminated buildings, remediation of soil and vegetation, changes in animal husbandry, monitoring the environment and produce, provision of clean foodstuffs, and waste management (ICRP, 2007). For decisions specifically involving environmental remediation and cleanup of the contaminated areas, a proper perspective on the potential risks involved is essential. In general, the optimization process weighs the potential future risks and other factors such as costs against the possible immediate benefits such as returning the populations to the affected areas. In the context of radioactive contamination, the risk is usually taken to mean the probability of potential human health effects occurring in the future as well as ecological impacts (Copplestone *et al.*, 2001) that may result from the existing exposure conditions following the radiological or nuclear incident. However, there may be many other risks to consider, including physical, biological and chemical hazards in the affected area, as well as risks that are inherent in the remediation process, including demolition, construction, transportation, and waste disposal.

Compiling a list of all risks in a comment context for comparison can facilitate decision making. A framework for such an approach is demonstrated in Till and Grogan (2008) and Till *et al.* (2012). For radiation, instead of characterizing exposure levels, it is preferable to make risk comparisons (Covello *et al.*, 2001). Following the Fukushima Dai-ichi NPP accident, IAEA (2011a) encouraged the Japanese authorities involved in the remediation strategy to balance cautiously the different factors that influence the net benefit of the remediation measures to ensure a net dose reduction. IAEA suggested that the focus should be on doses from likely exposure scenarios, not activity concentrations on (or in) the affected areas and environment. The investment of time and effort in removing contamination beyond certain levels from everywhere, such as all forest areas and areas where the additional exposure is relatively low, does not automatically lead to a reduction of doses for members of the public and can generate, unnecessarily, large amount of waste at excessive costs.

Both decision makers and stakeholders must also remember that the larger context of the risk assessment effort is to facilitate the timely recovery of the affected communities through the optimization process that is specific to the incident conditions, and that the incident-caused recovery action is to be governed by the protection principles developed for an "existing exposure situation," and not by restoration to exposures governed by the protection principles developed for a "planned exposure situation" (ICRP, 2007).

Experienced radiation risk assessment experts will be needed to evaluate exposures and potential exposures due to atmospheric transport, surface water transport, groundwater transport, terrestrial and aquatic food chains, and/or overall site conceptual pathways.

These assessments will drive risk management decisions that will in turn drive interim and final cleanup decisions. More in-depth discussions of these issues can be found in Till and Grogan (2008).

From the environmental monitoring data, scenarios can be developed to predict individual exposures. A summation of projected exposures could be made for individuals and the population, and a radiation risk assessment could be conducted. Then, options for mitigating exposures could be proposed, with an evaluation of each option based on cost, availability of remediation technology, and acceptability to the community. After the mitigation techniques have been applied, the exposures could be monitored again and the process repeated.

Strategies are needed that address multiple environmental sources of exposure (air, water and land), through multiple exposure pathways (direct gamma rays, inhalation, ingestion), from multiple radionuclides, with different emissions, different half-lives, and different retention times in the body. The assessment should attempt to address the challenging multi-source, multi-pathway, multi-radionuclide, and multi-risk issues. To estimate individual risk, consideration should also be made of age, gender, individual susceptibility, health status, and exposure potential.

Characterizing the risks must also include consideration of physical, biological and chemical hazards. There will be risks involved in restoring essential services, and careful planning is required to ensure that those risks are properly managed. Even collecting the household garbage from a contaminated area may pose risks from the nature of garbage beyond that of radioactive contamination (*e.g.*, the lack of electricity might lead to inadequate refrigeration and subsequent decay of organic material and growth of pathogens). Detailed consideration of the simple task of taking out the garbage might produce insights that lead to new best practices, or improvement of existing ones, which help minimize public health risks. Similar considerations for restoration of other essential services will help prepare industrial, commercial and residential property to be ready for people to return.

5.3.1.1 *Industrial Property.* While industrial property has many of the same restoration considerations as reflected in the essential services matrix (Figure 5.2), one important difference will be in the assumptions made about durations of exposure. If workers are coming into the contaminated area to work, they will not be in the area 24 h d^{-1}, although they may be in the area for >40 h $week^{-1}$. They can be provided uncontaminated drinking water and food, thus eliminating the ingestion pathway as a route of exposure. Direct gamma-ray exposure would still be a risk factor, but parking lots can be washed down with street sweepers to mitigate exposure levels. Roofs can be hosed down (with or without detergent) and the removable contamination can be washed away. By measuring the gamma-ray external radiation fields and the activity levels of airborne radionuclides, it is possible to estimate the radiation doses that the workers might experience. Then the workers could participate as a stakeholder group in the decision about their return and daily stay times on the job, or they may choose to have a union negotiate on their behalf.

Depending on the choices of decontamination technique, as well as choices about the containment of contaminated material (storage versus dilution if, for example, run-off is allowed to enter storm drains), there will be varying amounts of radioactive waste generated. The cost of disposal is one of the considerations in determining the best option for remediation of a particular industrial zone. A list of available decontamination techniques is summarized in Appendix C.

5.3.1.2 *Commercial Property.* Considerations for restoration of commercial property are similar to those for industrial property in terms of the assumptions for the time that workers will occupy the buildings, but there will be a different demographic and stay time for customers at the commercial establishments. While workers in industries are generally from 18 to 65 y of age, people that go to commercial establishments are likely to cover a broader age range including children, who are considered more radiosensitive than adults for some but not all tissues and organs (UNSCEAR, 2013). Customers may only shop for a few hours, ~2 to 4 h week^{-1}, thus limiting their time of exposure. Depending on the type of commercial establishment, the ingestion pathway may or may not be a consideration; different assumptions would apply for a dry cleaner versus a food store or candy shop. Individuals skilled in running exposure models will need to spend time with stakeholder groups, working out realistic assumptions for type and duration of exposure.

5.3.1.3 *Residential Property.* Many different exposure assumptions will prevail in the case of an urban landscape versus suburban or rural. Pet owners may have exposures different from nonpet owners, depending on the amount of time that the pets spend outdoors, and their propensity to pick up contamination on their fur and paws and bring it inside. There may be special instructions needed for people with gardens with regard to the types of vegetables grown to help minimize the potential for intake of radioactive material from the foods they produce. Totally different exposures would be considered if, for example, pumpkins for Halloween were the crop of interest versus tomatoes.

5.3.2 *Site-Specific Conditions*

Cleaning up an area that is affected by a major radiological or nuclear incident will depend on a number of site-specific conditions, which in turn are closely tied to the incident. As discussed above, many of the radiological concerns regarding late-phase recovery are associated with the contamination brought about by the incident, such as the contamination derived from deposition by the initial radioactive plume and the subsequent transport of contaminants through the environment.

There are a number of site-specific factors to be considered through the optimization process for late-phase recovery activities (Table 5.1). It is important to note that several of these factors are interrelated and therefore should be carefully evaluated together in the optimization. For example, setting the cleanup criteria affects the cleanup effort and generation of radioactive waste volumes, and thereby affects the potential costs involved. Thus for each factor considered, it is important to look into an array of potential viable options rather than one single option.

5.3.3 *Data and Information Requirements*

Several recent publications (Nisbet *et al.*, 2009; OECD/NEA, 2010) have described the type of ancillary information that will be needed to manage recovery effectively for accidents at NPPs. Some of the data can usefully be collected in advance but this would not necessarily be as practicable for nuclear or radiological terrorism incidents as there could be many different types of targets. For those deemed at highest risk, some gathering of information in advance would be worthwhile. A summary of the main issues and associated data and information requirements to be considered to support the development of recovery strategies is shown in Table 5.2. Geographic information systems can be used to map many of the criteria listed to highlight both the extent of the contamination and the scale of the recovery operation required.

5.3.4 *Environmental Risk Assessment Tools*

Responsible federal agencies have developed approaches and technical tools for use in the decision-making process both in emergency response and for consequence management. For nuclear or radiological incidents, assistance capabilities are maintained primarily by the DOE National Nuclear Security Administration. Such capabilities are complemented by monitoring and response capabilities operated by EPA:

- The Radiological Assistance Program is usually the first responding team from DOE for assessing the emergency/incident situation (FRMAC, 2010).
- The National Atmospheric Release Advisory Center provides special expertise and tools and services to map the

TABLE 5.1—*Site-specific factors to consider for optimization during late-phase recovery activities.*

Factor to Consider	Description	Relevance to Recovery	Site-Specific Considerations
Affected areas	Area identified as contaminated with radioactive material.	The affected area may be larger than the area identified for the remediation effort.	Size of the area is determined by the remediation criteria and future land uses.
Affected populations	Population groups that are affected by radioactive contamination include populations displaced by evacuation or relocation, and those hosting displaced residents.	The groups include people who are evacuated or relocated, as well as for those whose residences and businesses have been contaminated or affected by contamination.	Size of the evacuated or relocated population is determined by the magnitude of the incident and the radiological releases, as well as the population density in the affected zone. Special considerations are needed for handling disadvantaged populations.
Affected infrastructures	Affected infrastructures that are necessary for the recovery of affected communities.	Restoring critical infrastructures is key to recovery and therefore will be a focus of the remediation effort.	The availability of key infrastructures to the affected communities is a priority for recovery. These include major highways, energy distribution systems, and others necessary to provide essential services (Figure 5.2)

Projected land use	Future land-use options for the affected areas that require remediation.	The remediation decision will be based on the viable future land-use options.	Stakeholders within the affected communities will be involved in prioritizing the future land uses of the contaminated areas.
Type of contamination	Other than radioactive contamination, the incident may also involve toxic chemicals or other hazardous materials (*e.g.*, Bird and Grossman, 2011).	Special effort and consideration would be needed when the contamination involves other than radioactive materials.	Potential contamination to local infrastructure such as drinking water sources, or management and disposal of the various types of waste could be site specific.
Human health risk	Human health risk associated with the incident is a major concern to the populations affected.	The decision on remediation criteria is directly related to the concern on human health risk.	The site-specific optimization process will incorporate human health risk into the consideration.
Ecological risk	The radioactive contamination may affect sensitive ecological systems near the incident site.	The decision on remediation will take into account the potential impact to the ecological system (*e.g.*, UNSCEAR, 2011).	The affected sensitive ecological system could be site specific.

TABLE 5.1—(*continued*)

Factor to Consider	Description	Relevance to Recovery	Site-Specific Considerations
Preservation of places of national or regional significance	Affected places or structures that represent national or regional iconic significance.	Speedy restoration of the affected sites may be a desirable action, especially following a terrorist attack.	Special preservation techniques that delay implementation may be required. Contamination of the sites may affect tourism and the local economy as well as population morale.
Technical feasibility	Cleanup technologies are required for the cleanup effort.	Availability and feasibility of the cleanup technology will determine the performance of the cleanup effort.	Cleanup technology varies considerably with affected areas, including urban, suburban and rural areas, and therefore the use of technology will be highly site specific.
Radioactive waste generation and management	Some amount of radioactive waste will be generated by both the incident and the subsequent decontamination effort.	The amount of waste generated will be associated with the cleanup criteria and the technology used.	Different land-use considerations will affect waste volume generated as well as locating temporary waste storage and final disposal sites.

Costs for cleanup	Costs remain the primary constraint for the recovery effort.	The considerable undertaking in cleanup requires adequate funding.	Costs will be closely tied to the cleanup goal: land-use decisions, technology, and radioactive waste management could be site specific.
Economic considerations	The recovery of the affected region hinges on the vitality of the local economy.	A thorough and timely cleanup will ensure a healthy economic recovery of the affected region.	Stakeholders will be involved in prioritizing the cleanup goal in order to optimize the economic recovery.
Timeliness of cleanup	A smooth recovery of an affected community must be conducted in a timely manner to ensure vitality of the area.	Time consideration is crucial to recovery; therefore a timely cleanup effort is important.	The urgency of recovery will be determined by involving stakeholders in the planning for cleanup.
Short- and long-term effectiveness	Short-term options may include stabilization of contamination "on-site" (*i.e.*, at the source of the nuclear or radiological incident) rather than the removal of contamination on the long-term basis.	Cleanup goals may influence the effectiveness of the effort for the short or long term, depending on several factors including the availability of technology and suitability of the cleanup approach.	A site-specific cleanup approach will determine the emphasis on short- or long-term effectiveness of cleanup.

TABLE 5.1—(*continued*)

Factor to Consider	Description	Relevance to Recovery	Site-Specific Considerations
Public acceptability	Any cleanup decision must be acceptable to members of the public.	Cleanup goals require stakeholders' involvement. It is a key element in the optimization process.	Site-specific cleanup goals will be made with participation from stakeholders to incorporate site-specific issues properly.
Cultural and ethnic factors	Any cleanup decision should take cultural and ethnic diversity into consideration as part of stakeholder outreach efforts.	A balanced stakeholder outreach should include cultural and ethnic considerations to reach a balanced viewpoint in cleanup goals.	Considerations are to be given to the cultural and ethnic aspects of the affected communities in order to achieve a balanced stakeholder decision.
Socio-political factors	Socio-political influence is a definitive factor in decision making. Experience from past incidents attests such an influence on the recovery process.	The socio-political input is among other factors to be considered for the optimization process in recovery.	As can be expected, any decision regarding cleanup will likely be strongly influenced by local political opinions.

TABLE 5.2—*Data and information requirements to facilitate recovery after a major nuclear or radiological incident in inhabited areas and food production systems.*

Topic Area	Specific Issue	Data and Information Requirements
Inhabited areas	Population	• Distribution and size in affected area • Identification of sensitive subgroups based on age, health, social/ethical considerations as well as institutionalized people such as prisoners, senior citizens, hospital patients • Numbers of people relocated • Resources for temporary accommodation
	Types of buildings	• Type of property and construction (*e.g.*, multi-story, detached) in affected areas • Proportion of residential, public, industrial and commercial buildings • Presence of listed or protected buildings or places of historical or cultural significance
	Critical buildings and infrastructure	• Critical facilities and infrastructure such as schools, hospitals, water treatment plants, sewage treatment plants, roads, and railways • Prioritization and interdependence
	Waste disposal facilities	• Location of sites licensed to receive contaminated waste, including authorized limits • Numbers, types and capacities of facilities • Transportation routes to disposal facilities

TABLE 5.2—(*continued*)

Topic Area	Specific Issue	Data and Information Requirements
Food production systems	Agricultural	• Availability and access to databases identifying producers and subsequent food supply chain
Waste disposal facilities	Domestic	• Information on the location, scale and importance of domestic food production (allotments, small holdings)
	Free or wild foods	• Information on scale and importance of free/wild foods in the area, at key times of the year
	Hunting and fishing	• Availability and access to databases identifying people with licenses for fishing and hunting in the area • Location of sites licensed to receive contaminated waste from cleanup, including authorized limits • Numbers, types and capacities of facilities • Transportation routes to disposal facilities • Arrangements for communications *via* local/national television, radio, websites, social media
Communications		• Provision of information to consumers: pre-prepared leaflets, fact sheets, briefing packs, press releases • Provision of information and instructions to implementers of protective actions • Arrangements for requesting and claiming compensation for those likely to incur financial losses

Drinking water supplies	Sources	• Identification of drinking water sources in a given area and an assessment of their sensitivity to contamination and timescales • List of extraction points for each source
	Monitoring	• Availability of monitoring facilities, turn-around time, capacity for different analyses • Identification of key monitoring points in the distribution system
	Alternative supplies	• Sources of alternative supplies: bottled water, tankers
	Water treatment	• List of where each source is treated and type of treatment in place

spread and impacts of hazardous materials released into the atmosphere.

- The EPA Airborne Spectral Photometric Environmental Collection Technology has chemical, radiological and situation awareness (imagery) capabilities to detect, measure and track radioactive material and hazardous chemical releases.
- The Aerial Measuring System provides the capability to detect, measure and track radioactive materials released in an emergency to determine contamination levels.
- The Radiation Emergency Assistance Center/Training Site provides around-the-clock assistance (including personnel and equipment) for direct medical care of victims and responders in a radiological emergency.
- The Armed Forces Radiobiology Research Institute provides education on medical effects of ionizing radiation, maintains a Medical Advisory Team and provides forms and software tools useful in the response to a nuclear or radiological emergency.
- The EPA Environmental Response Team is a group of EPA technical experts who provide around-the-clock assistance at the scene of hazardous substance releases, offering expertise in such areas as treatment, biology, chemistry, hydrology, geology and engineering.
- The EPA Radiological Emergency Response Team is a specialized unit that responds to emergencies requiring the cleanup of radioactive materials. They provide on-site and laboratory-based risk monitoring services.
- The EPA Chemical, Biological, Radiological, and Nuclear Consequence Management Advisory Team provides scientific support and technical expertise for decontamination of buildings, building contents, public infrastructure, agriculture, and associated environmental media. Specialized expertise, such as biochemistry; microbiology and medicine; health physics; toxicology; heating, ventilation, and air conditioning engineering; and industrial hygiene, is available to assist local, national and international agencies supporting hazardous substance response and remedial operations, including nationally-significant incidents.
- The Federal Radiological Monitoring and Assessment Center (FRMAC, 2010) coordinates and manages all federal radiological environmental monitoring and assessment activities during a nuclear or radiological incident, and supports federal, state, tribal and local governments. DOE leadership transfers to EPA for the long-term recovery activities.

- The Advisory Team for Environment, Food and Health is a radiological emergency response group tasked with providing protective action recommendations to state and local governments on behalf of its member agencies. The permanent membership includes representatives from EPA, the Food and Drug Administration (FDA), the Centers for Disease Control and Prevention (CDC), and the U.S. Department of Agriculture. This group receives the monitoring data from FRMAC to develop its recommendations.

These capabilities are maintained by the DOE National Nuclear Security Administration and EPA to address the issues associated primarily with the early or intermediate phases of the incident. The radiological monitoring and assessment capabilities represented by FRMAC carry special importance in transitioning into the late-phase recovery activities. To this end, FRMAC has developed technical approach and computer models (DOE/NNSA, 2014; FRMAC, 2010) for interpreting environmental measurements and predicting doses to members of the public, and making recommendations in accordance with the Protection Action Guides (PAGs) issued by government agencies (EPA, 1992; FEMA, 2008), which currently address only the response to early- and intermediate-phase actions.

In addition, DOE also provides tools and technical bases for the derivation of guidelines (Yu *et al.*, 2009), which include the RESRAD-RDD computer software. The software is used to calculate incident-specific guidelines and response workers' stay-time tables for access control (relative to the appropriate PAGs), and dose-based soil and building contamination levels to assist in site-specific optimization decision (DHS, 2008a). As discussed below, RESRAD-RDD is a member of the RESRAD family of codes (Yu *et al.*, 2009) designed to estimate radiation doses and risks from contamination with residual radioactive materials from an RDD incident. Among these tools, the RESRAD-BIOTA computer software specifically addresses the ecological risks (DOE, 2004).

In general, these methods and tools have been used for site remediation within the context of environmental cleanup of a defined area of contamination. Exact application of the methods for assessment of contamination caused by radiological and nuclear incidents needs to be further evaluated, especially if the contamination is widely spread (Chen and Tenforde, 2010).[5]

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[5] Nisbet, A. and Chen, S. (2013). "Decision making for late-phase recovery from nuclear or radiological incidents: New guidance from NCRP," presented at the ICRP 2013 Commission Meeting in Abu Dhabi (Illinois Institute of Technology, Chicago).

However, it should be noted that certain issues remain unresolved and require further investigation, particularly for the cleanup of a contaminated urban environment (as may be favored for terrorist attacks). For example, while the FRMAC procedures deal with dose assessment in the early and intermediate phases, the procedures do not specifically cover the late phase. There also remains a need to develop a national consensus method for dose projection inside buildings following an RDD incident (Sullivan *et al.*, 2008). Detailed protocols for dose assessment in urban settings should be developed prospectively so that decision makers associated with late-phase recovery efforts can become fully familiar with the process and its products.

5.4 Establish Goals and Identify Options

Decision making involves establishing goals and identifying and evaluating available options. Consequently, numerous considerations, especially site-specific conditions, need to be carefully assessed. Decision options may include not implementing any management options.

Decision-making methods depend on having alternatives to examine, so that the best available options can be selected and evaluated. As a consequence, the first step in the process is to identify goals and present viable alternatives. These goals and alternatives need to be developed with the stakeholders. Some of the key decisions to be considered are discussed in Section 4.3.

5.4.1 *Establishing Goals*

Priority for recovery should focus on maintaining and enhancing the overall resiliency of the affected community. It is extremely important that members of the public participate fully in establishing the goals for recovery. As discussed in NCRP Report No. 146 (NCRP, 2004), stakeholder participation results in a greater sense of fairness in the outcomes. Based on the decisions made for remediation, some individuals may be made better off after the recovery, while others may be worse off. Thus, it is crucial that discussions of these possibilities are held and that the affected individuals are included in the talks.

5.4.1.1 *Variety of Goals*. There are various goals that could be considered, including reducing the possibility of exposure to radioactive materials, reducing job loss, reducing the loss of property values, protecting sensitive populations, speed of recovery, and others (ICRP, 1977).

Milestones should be developed so all can determine whether or not the goals are being met. Monitoring, whether of radiation or employment or some other relevant indicator, can then be used to assess whether goals are being achieved. If not, then the methods used should be re-examined and new methods adopted if deemed more effective. A flexible, iterative optimization approach is essential for the recovery process to succeed.

The optimization approach necessarily entails evaluation of viable alternatives from which key information can be obtained to aid in decision making. The alternatives identified will be influenced by the cleanup criteria selected. For example, a stricter criterion will require a more extensive cleanup effort and so prolong the cleanup schedule, increase costs, and generate increased quantities of waste. The increased waste may increase the potential for exposure to members of the public due to transportation and result in significant environmental trade-offs, and so the optimization approach must be all-encompassing.

While getting industry up and running again may be a primary goal, the economy also depends on having secondary businesses (*e.g.*, shops, restaurants, dry cleaners, gyms, hardware stores, florists, hair salons) restored. Restoration of the industrial and commercial sector depends on having places where workers can live. Therefore, restoration of the residential areas (*e.g.*, schools, parks, soccer fields) is also necessary to re-establish the sense of community.

While restoration of economic viability is always among the priority items for recovery, other factors also need to be considered, particularly psychological and political issues that often drive the decision-making process. For example, a rapid recovery of affected iconic national symbols, such as historic structures or monuments, may be placed on the top priority list for psychological reasons despite limited economic benefits.

Future uses of the area need to be considered as well. Will it be reasonable to seal off the affected area in order to develop other areas? Or is it more important to clean the affected area so that it can be used for its original purpose? Do the stakeholders want the area to be rebuilt as it was, or is this a time to consider different urban structures? Discussions in New Orleans after Hurricane Katrina suggest that these alternatives may be important to have as options (Kates *et al.*, 2006).

During a reconstruction effort, it may be desirable to incorporate additional resiliency measures to provide members of the public with protection from other types of possible future disasters. For instance, if infrastructures such as water/sewer/electricity/telecommunications need to be reconstructed, it may be cost effective to design them to withstand anticipated floods, storm surges, or other natural disasters. Designing resiliency should not be limited to resiliency to the particular type of disaster experienced (*i.e.*, nuclear or radiological incidents), but should include whatever catastrophic incidents could reasonably be expected to occur (*i.e.*, 100 y floods). This is particularly important if public funds are expended during reconstruction, since it would not be in the public interest to reconstruct an area for rehabilitation only to have it succumb to another disaster soon thereafter.

5.4.1.2 *Long-Term Health and Environmental Protection*. One of the key goals of a long-term recovery program is to reduce chronic exposures to environmental contamination and to restore, to the extent possible, a sense of normality to the affected population. This includes not only a reduction in the risks associated with exposure to radiation but also the psychological burden resulting from the disruption of people's lives due to contamination, relocation, and loss of property and livelihood as well as the fear of the possible consequences of radiation exposure (Bromet, 2014; Slovic, 2012).

5.4.2 *Identifying Options*

Once the land uses affected and the pathways of exposure are identified, options to reduce doses need to be determined. The remediation strategy selected will depend on the agreed upon goals. Populations displaced as a result of the early-phase evacuation(s) will likely want to reoccupy their apartments, homes, shops, offices, and other buildings as quickly as reasonably possible, but a phased return through partial cleanups until full functionality can be achieved may be necessary. Caution needs to be exercised during remediation to avoid generation of secondary waste (such as contaminated water used in cleanup activities) and recontamination of the environment (from improper confinement of the generated waste). The following subsections give an overview of the range of recovery options available; the classification is based on that given by Nisbet *et al*. (2009).

5.4.2.1 *Options for Inhabited Areas*. Recovery options for inhabited areas can be divided into two main groups: options that shield people from the contamination (shielding options) and those that remove contamination (removal options, also called decontamination or cleanup options). The implementation of recovery options is generally the responsibility of the authorities. However, self-help actions, which may be implemented by the affected population, can be useful. It is important to note that the option not to carry out any recovery can be a valid alternative.

5.4.2.2 *Shielding Options*. Shielding options can be used to reduce both external exposure and the intake of radioactive material, but are usually primarily effective in providing protection against only one or the other of these exposure pathways. The use of shielding materials is potentially a very effective option for radionuclides emitting alpha or beta particles, particularly if they are relatively short-lived. Some more permanent shielding options, such as burial of contaminated material are effective for both external exposure and intakes of long-lived and gamma-ray-emitting radionuclides.

5.4.2.3 *Types of Shielding*. In the context of late-phase recovery, there are three main types of shielding: burial and covering of objects, removal and storage of objects, and fixing contamination in place.

If the primary aim is to reduce external exposure, shielding materials can be placed between the contamination and people (*e.g.*, by burial and covering of objects). Examples include the use of clean topsoil in gardens and other open areas and the turning of paving slabs. In general, these types of options are more effective in reducing external dose rates from radionuclides emitting beta particles than for radionuclides emitting gamma rays. Inhalation doses from resuspended material are also reduced while the shielding material is in place.

Reduction in external exposure can also be obtained by restricting access to contaminated areas or objects. In this case, air acts as the shielding medium. Such options are 100 % effective against all radioactive contaminants while they are in place, as people do not receive any dose from the area from which access is restricted.

If the primary aim is to protect against the intake of radioactive material, shielding is used to fix the contamination to the surface and restrict its mobility. Fixing options also have some benefit of providing shielding from external exposure but the effectiveness of the shielding is likely to be secondary to the dose reduction achieved for internal exposure. Furthermore, removal of fixing materials as part of decontamination efforts can also remove some of the underlying contamination held on the surface as dust.

5.4.2.4 *Removal Options*. Removal options involve the decontamination or cleanup of contaminated surfaces and objects. One of the main disadvantages is that contaminated waste material is produced, often in large quantities. There may also be major constraints on the use of removal options on historic buildings or buildings that are in poor condition where unacceptable damage to the structure or character of the buildings may occur. For example, high-pressure hosing and sandblasting may cause significant damage to old or poorly maintained brick or stone buildings (see discussions in Appendix C for available decontamination technologies).

Similarly, it may not be feasible to carry out decontamination techniques that directly affect the surfaces of objects due to the damage that such techniques may cause. For example, this may be particularly true for objects found in heritage buildings and museums. These objects may, however, withstand gentle washing or vacuuming without causing damage to their surfaces. It is likely that disposal of such objects will be unacceptable because of their monetary or heritage value, and therefore, if all decontamination techniques prove unacceptable or impracticable, storage or shielding of the objects could be considered. It should be recognized that these objects would contribute relatively little to the dose and their cleaning would therefore often have the primary purpose of public reassurance (Appendix C).

5.4.2.5 *Self-Help Actions*. Self-help actions are simple measures that may be carried out by people living in the affected areas rather than by skilled workers and that generally require no specific expertise or experience to implement. After the Chernobyl nuclear reactor accident, self-help programs introduced in the highly contaminated areas of the former Soviet Union have generally been perceived positively by the affected populations (Beresford *et al*., 2001).

As documented by the IAEA mission on remediation of large contaminated areas off-site from the Fukushima Dai-ichi NPP (IAEA/NEFW, 2011) volunteers may wish to take it upon themselves to remove contamination from key areas. In Japan, volunteers, mostly the parents of pupils, took an effective self-help step of cleaning up schools before pupils were permitted to return. These efforts require technical support and guidance from experts if they are to be effective but development and provision of such guidance adds to the resiliency of the population.

5.4.2.6 *Decision Not to Implement Any Recovery Options*. In some circumstances, the best course of action might be to not implement any recovery options. If this decision is taken, it should be accompanied by a monitoring strategy. Table 5.3 gives the main advantages and disadvantages of not implementing any recovery options.

5.4.2.7 *Options for Food Production and Drinking Water Supplies*. Numerous recovery options were developed as a result of the Chernobyl nuclear reactor accident and some of these have been adapted and improved for site-specific conditions following the accident at the Fukushima Dai-ichi NPP (IAEA, 2006a; 2006b;

TABLE 5.3—*Advantages and disadvantages of not implementing any recovery options.*

Advantages
• Implementing recovery options, if only to provide reassurance, will likely be perceived as indicating that there is a problem even if doses are negligible and members of the public may be reluctant to return to their homes. • Perception of the affected area from the outside may be better (*i.e.*, incident is not perceived as a real problem; people are living normally), so economic loss and stigma may be reduced. • No waste is produced. Some cleanup options that may be undertaken for public reassurance can create a lot of contaminated waste (*e.g.*, grass cutting and top soil removal). • Promotes return to normal living in the area.
Disadvantages
• It requires very good communication with the community to convince people that risks are low or negligible and that they should accept the decision to not implement recovery options. • Opting out of remediation should be linked with a rigorous monitoring strategy. Such a monitoring strategy, however, might not be time- or resource-effective compared with the implementation of recovery options. • Not implementing any recovery options may send a message that responsible organizations do not care about the community. • Decision makers will need to define and justify the boundaries of the area in which recovery options are not implemented. • If restrictions have been placed on food consumption, there will need to be careful explanation of why these are required while no action is taken to deal with the contamination in inhabited areas.

2006c; 2011a). The options include those directed at drinking water supplies, the soil-to-plant pathway, and intervention in animal production systems.

5.4.2.7.1 *Intervention along the soil-to-plant pathway.* These options aim to remove contamination completely from the food chain (*e.g.*, topsoil removal); to reduce soil-to-plant transfer of the radionuclide by physical or chemical means (*e.g.*, plowing, fertilizer, and lime treatments); to reduce the volume of contaminated crops requiring disposal by feeding contaminated food to animals that are not immediately destined for consumption or otherwise to the marketplace.

5.4.2.7.2 *Intervention in animal production systems*. These options aim to remove contaminated animal products completely from the food chain (*e.g.*, slaughter); to reduce ingestion of contaminated feed by livestock by management of their feeding regime (*e.g.*, clean feeding, selective grazing) and manipulation of slaughter times; to reduce gut uptake of the radionuclide (*e.g.*, administer Prussian blue, calcium, clay minerals to feed); to reduce waste by diverting contaminated milk to cheese or powdered milk and waiting for the activity of the radionuclides to decay; to provide reassurance to consumers that contaminated animal products are not entering the food chain (*e.g.*, real-time monitoring). Such monitoring may be considered a support measure rather than a recovery option in its own right and used as an adjunct to various other measures to demonstrate their effectiveness.

In order to reduce radionuclide uptake by fish, it is possible to intervene at three points in aquatic systems: physically prevent radionuclides reaching lakes by construction of barriers and dikes; reduce uptake by fish by dilution of radiocesium and radiostrontium in lake water by adding calcium (lime) and potassium; and reduce ingestion of contaminated feed by supplying clean feed to farmed fish.

5.4.2.7.3 *Intervention in drinking water supplies*. To reduce the levels of radionuclides reaching the drinking water supply, it is possible to intervene by providing an alternative water supply (*e.g.*, bottled water), changing water extraction points, blending with clean water, and removing water contamination at treatment plants (through normal water treatment or introduction of enhanced systems) or at the tap (filtration).

5.4.2.7.4 *Reassurance*. While many recovery options are of a technical nature involving some form of physical or chemical intervention to reduce transfer of radionuclides in the food chain, a few options can be considered to have more societal relevance (*e.g.*, the provision of advice, reassurance and information to members of the public, as well as support for self-help actions).

5.4.2.8 *Waste Disposal Options*. Considerable volumes of contaminated waste can be generated as a result of restrictions on crops, milk and meat. As these restrictions are based on statutory requirements, it is essential to identify appropriate waste disposal options in advance. These range from relatively simple *in situ* methods (plowing in, composting, and land spreading) to off-site commercial treatment facilities (*i.e.*, landfill and incineration) (Appendix B).

5.4.2.9 *Options for Forest Areas*. Decontamination of forest areas is likely to be of low priority, due to the low probability of population exposure. Some options include placing restrictions on access, harvesting food items such as mushrooms and berries, hunting, and collection of firewood, and increasing fire prevention. The transfer of radionuclides to wood can be limited either through reducing plant uptake by application of fertilizers and lime or by carefully selecting times for harvesting the trees. While the removal of fallen leaves may reduce recontamination of the soil, subsequent leaf disposal can lead to contamination of other areas. Also, if the residual activity of the radionuclides is taken up by trees, leaves in subsequent years may need to be screened before burning, burying, mulching or composting.

5.5 Evaluating Options

To best achieve the goals of recovery, discrimination criteria among alternative options should be:

- able to differentiate among the alternatives;
- complete and include all goals;
- operational and help decision makers focus on the implications of the alternatives;
- nonredundant; and
- few in number to keep the problem manageable.

Considering the information discussed in Sections 4.2 and 5.3, alternative options to meet the goals of recovery need to be evaluated. All key attributes should be documented for the various options, and the results compared. This process will provide the basis for decision making.

Once the alternatives have been identified and screened for their ability to meet the goals agreed upon, criteria for evaluating the alternative options should be set. As discussed in Section 4.2, these criteria should allow decision makers to discriminate among the alternatives. The 'best' alternative will be the one that most closely achieves the agreed upon goals.

As discussed in Baker *et al*. (2001), criteria should have five characteristics:

- discriminate among the alternatives available;
- include all goals;
- help the decision makers focus on the implications of the alternatives;
- be nonredundant (*i.e.*, not address the same issue); and
- keep the problem manageable.

With the criteria in place, the appropriate tool(s) to select among the alternatives can be chosen. Several possible options are discussed in Section 5.3.4. Each tool has strengths and weaknesses that need to be evaluated carefully.

The criteria then need to be quantified for each of the possible alternatives. The metric for each can be different, but need to be consistent across the alternatives. For example, cancer risk under each alternative might be estimated as the potential increase in deaths due to radiation and perhaps other exposures, while employment in a sector under each alternative might be measured in hours worked per week. It is crucial that these criteria are measured using the best available information. This step in the process will require the help of experts in various fields, who will need to work with the decision makers to be sure that the criteria as measured are understood by all.

The alternatives can then be ranked by applying the chosen decision-making tool(s) to the criteria. How the criteria are weighted will be an important part of the process. If any of the criteria involve uncertainty, sensitivity analyses might be conducted. This process evaluates the alternatives under different assumptions about the selection criteria, and can help decision makers better understand the impact of the different outcomes.

5.5.1 *Technical Approaches to Supporting Decision Making*

State-of-the-art technology and methods should be made available to support late-phase actions. More importantly, a complete compilation of such information should be made available and evaluated for their applicability and/or efficacy. This section will describe some technologies and analytical methods that are important to support the decisions made for late-phase cleanup actions.

5.5.1.1 *Cost-Benefit Analysis*. Cost-benefit analysis is a centerpiece to support the principle of optimization as recommended by ICRP (1980; 1991; 2007). Specifically, ICRP Report No. 37, *Cost-Benefit Analysis in the Optimization of Radiation Protection* (ICRP, 1980), discusses the technical approach and considerations necessary to support the implementation of the optimization approach (Appendix D.2). Stakeholders must be involved in the process, helping to identify costs and benefits. They may also help to specify the dollar values of costs and benefits.

Cost-benefit analysis is frequently used when making decisions about which policy option to undertake. Since choices will have to be made among the various options when moving into late-phase recovery, cost-benefit analyses become a reasonable strategy.

The optimization rule in this strategy is to choose the option that maximizes net benefits. Thus the benefits of the option, as well as the costs, must be obtained and monetized. If the costs and/or benefits are spread over time, then the stream of dollar values must be discounted appropriately. This is meant to mimic, to some extent, the process that happens in a free market. When the supply of a good is equal to the demand for the good, then the net benefits are maximized.

In ICRP Publication 37 (ICRP, 1980), the cost-benefit process is discussed for the scenario of choosing an optimal level of radiation protection. In this scenario the equation (Equation 5.1) to be maximized is:

$$B = V - (P + X + Y)\,, \tag{5.1}$$

where:

B = net benefit of the introduction of a practice

V = gross benefit of the introduction of such practice

P = basic production cost of the practice, excluding the cost of radiation protection

X = cost of achieving a selected level of radiation protection

Y = cost of the detriment resulting from the practice at the selected level of radiation protection

The practice that maximizes "*B*" is chosen. In this case, the benefits are taken to include all the benefits accruing to everyone in society and not just those received by particular groups or individuals. Costs are considered as comprising the total sum of all negative aspects of an operation, including monetary costs and any damage to human health or to the environment.

The calculation of some costs and benefits is relatively straightforward. This is true in the case of marketed goods (*e.g.*, bottled water is sold in stores so its value is known). Other costs and benefits are more difficult to quantify (*e.g.*, a reduction in cancer risks some years in the future). However, the economics literature does provide guidance on how to monetize nonmarketed goods.

Discounting is to be applied in the case when costs and/or benefits occur over time, which is very likely the case in late-phase recovery. Choosing an appropriate discount rate can be a part of the discussion with stakeholders.

The cost-benefit technique does not consider equity issues. However, when calculating costs and benefits it is possible to elaborate on which group or groups bear the costs and which group or groups receive the benefits. Vertical equity [those who are different in some dimension (such as income) being treated differently] and horizontal equity [those who are similar in some dimension (such as income) being treated similarly] can be discussed with the involvement of stakeholders.

5.5.1.2 *Other Economic Models*. There are several other economic models that can be used to assist in the decision-making process. Each has its own strengths and weaknesses. It is possible that several models will be used and the results of each can be included in the evaluation process [Appendix D (Appendices D.3 and D.7) provides further discussion of a variety of economic tools].

One often used computational model is the computable general equilibrium (CGE) model that incorporates the supply and demand from many different markets (*i.e.*, markets for various inputs and outputs, the market for labor) and models the markets when they are simultaneously in equilibrium. The model can be used to examine what the outcome would be if, for example, the ports that receive and send the goods are temporarily disrupted. Because there are multiple markets under consideration, other markets can respond, often through price changes, to the incident. The model can also be used to inform decision makers on what markets are likely to be affected by an incident, and to consider ways to minimize the impact of the incidents.

This CGE model has been used to examine the impact on the economy of various incidents such as the September 11 terrorist attacks and the Hurricane Katrina natural disaster, as well as hypothetical incidents such as terrorist attacks on the ports of Los Angeles. Using these models before an incident could help policy makers understand how best to prepare for such an incident.

However, these economic models do not include the impact of the incident in terms of health risks or environmental impacts.

There are other types of models that can be used to evaluate options. As discussed in ICRP Publication 37 (ICRP, 1980), there are multi-criteria methods that consist of a pairwise comparison between two options. The "better" option is chosen, then that option is compared to a third and so forth. What determines "better" will vary by the model. There are some models where "one option is considered better than another if the number of criteria for which it is better is sufficient, and if for the remaining criteria the differences are not excessive" (ICRP, 1980). Models of this type, which include pros and cons analysis, are discussed in Appendix D.5.

There are also aggregative models, which quantify the values of the criteria into one value, which is then used to rank the options.

These models assume that the criteria can be quantitated in some reasonable way and that weightings of the criteria can be agreed upon. An example of this type of model is the Multi-Attribute Utility Theory, discussed in Appendix D.3.

5.5.2 *Stakeholder Involvement in Evaluating Options*

The stakeholders' role in the decision process for establishing priorities for cleanup alternatives is to identify the social or political considerations which lead to the acceptance of a particular option. The challenge is to ensure that relevant socio-political considerations are effectively included in the decision process. In the following section, potentially-relevant socio-political impacts are identified and discussed. Although prior experiences may be drawn upon to identify the types of issues that may arise, it will be the affected population who determines acceptability of the selected options. The decision process will not be based wholly on a scientific assessment of safety from a health-risk perspective. Rather, the availability, effectiveness, feasibility and cost of remediation techniques, and options for alternative land use must be taken into account. Cleanup alternatives must be agreeable on a variety of scales and must be seen to have value for the entire community.

5.5.2.1 *Holistic Approach*. The influence of socio-political factors may occur on a variety of scales that can reinforce or negate each other. A holistic approach is important in the decision process to allow these socio-political factors to be recognized and addressed. Three levels of impact can be distinguished: national/global, local/regional, and individual.

The recovery phase will necessarily be focused on the immediate area that is affected and for which the cleanup alternatives are being evaluated and prioritized. The stakeholder involvement process will engage representatives from all sectors of local and regional communities to provide input and feedback on the cleanup alternatives that have been identified. There will be socio-political factors associated with ensuring the community infrastructure can be re-established (Section 5.4.1.1) and be viable; these will be accompanied by time pressures to restore the affected society to a new normality under various constraints the society may be facing. These constraints may include economics, ethics, and other concerns that may arise from local specifics. The presentation of cleanup alternatives should acknowledge the possibility of a no-return option in the incident (*e.g.*, that a feasible cleanup alternative cannot be identified or is considered unacceptable and, as a result, would spur the formulation of options for relocation to alternative areas).

The stakeholder engagement and communication effort must also engage all the organizations, institutions, communities and individuals who are affected less directly but can still exert a major influence on decision alternatives. One example could be a nearby community's refusal to accept produce or materials from the contaminated area even if they meet established safety standards. The optimal protection strategies and cleanup alternatives may be perceived differently by the population living outside the contaminated area from those living inside it. For this reason different decontamination options may have different levels of acceptability in different areas. Thus, socio-political factors distant from the recovery area also need to be identified and considered in the decision process.

Essentially the same tools and methods designed to promote effective communication and provide access to accurate, up-to-date information should be available to everyone regardless of distance from the impacted area. Ultimately, however, the affected population has to have control of the decisions that directly affect them.

The decision process needs to recognize the distinction between the community-level decision process regarding cleanup alternatives and the acceptance on the individual level to physically return to a residence, school, business, or public area that was affected by the radiological or nuclear incident. While the decision process will strive to allow normal operations to proceed, it is the individual's right to choose whether he or she will return to these affected areas to live and/or work. Socio-political influences will be more positively received if an individual's return decision is optional. This is in direct contrast to mandatory evacuation decisions.

5.5.2.2 *Whole-Community Approach*. In recent years, a growing concern has arisen over civil preparedness against major disruptions caused by natural disasters or terrorist acts. Recognizing the limitations of the government's role and its effectiveness in responding to such major incidents, FEMA began to develop a concept that involves the whole community in preparedness for such situations that states:

> "However, today's changing reality is affecting all levels of government in their efforts to improve our Nation's resilience while grappling with the limitations of their capabilities. Even in small- and medium-sized disasters, which the government is generally effective at managing, significant access and service gaps still exist. In large-scale disasters or catastrophes, government resources and capabilities can be overwhelmed" (FEMA, 2011b).

The whole-community approach advocates further engagement with stakeholders in the overall response effort. To this end, FEMA is initiating a national dialogue aimed to determine the best means by which residents, emergency management, practitioners, organizational and community leaders, and government officials can collectively understand and assess the needs of their respective communities. The approach follows three principles:

- understand the basic needs of the whole community;
- engage and empower all parts of the community; and
- strengthen what works in those communities on a daily basis.

The approach is also supported by the following strategic themes:

- understand community complexity;
- recognize community capability and specific needs;
- foster relationships with community leaders;
- build and maintain partnerships;
- empower local actions; and
- leverage and strengthen social infrastructure, networks and assets.

Additionally, the whole-community approach further integrates the element of empowerment with stakeholder engagement for preparedness and response to disasters. The concept applies throughout all phases of an incident, and will be particularly important to the late-phase recovery effort since there will be considerably diverse and complex issues that will involve a broad base of stakeholders in the optimizing decision-making process. Advancing such a concept also necessitates related actions by the government and responsible authorities to develop and adopt appropriate policies to facilitate and implement the approach. Such policies may include the creation and support of self-help programs as a means to engage and empower citizens in the aftermath of a disaster.

5.5.2.3 *Dynamic System.* By its very nature, a major nuclear or radiological incident will result in a unique set of cleanup challenges for which a well-prescribed solution is unlikely to exist. The inevitability of an evolving knowledge base requires the use of an adaptive management framework for making decisions. The most successful outcomes will be achieved by using a decision framework that is based on current data and information, is transparent, provides access to the supporting information, and is sufficiently flexible to allow changes if necessary. Although it is often stated that cleanup decisions will not be based on health risk alone, the importance of ensuring that human health risks and the efficacy of cleanup alternatives are evaluated using sound science and that the influence of uncertainties in these measurements on decisions is clearly presented cannot be stressed enough.

5.5.2.4 *Fear*. Risk perception regarding radiation exposure is likely to be an overriding factor affecting the cleanup decision process because of the intense public fear of radiation (Bromet, 2014; Slovic, 2012; Slovic *et al.,* 2001). Radiation is invisible, silent and odorless and can only be detected with specialized equipment. Because it is unfamiliar and poorly understood by most people, it is treated much more cautiously than other more familiar sources of risk.

The goal is to have all stakeholders understand the nature and magnitude of the health risks associated with the various cleanup alternatives, so that they can make an informed evaluation of the acceptability of specific options. This can only be achieved through an effective communication process that is open, honest and transparent (Covello, 2003; 2011a; 2011b; 2011c).

The degree of receptiveness and acceptance for different cleanup options will depend on the clarity with which the issues are laid out, how understandable the information is, and the anticipated consequences for each alternative. Sources of uncertainty influencing the decision process have to be articulated clearly and thresholds for acceptable or tolerable levels of uncertainty explained.

5.5.2.5 *Psychological Impacts of Terrorist Incidents*. The intrinsic characteristics of radiation (*e.g.*, imperceptibility to the senses and potential for cancer following a long latency period of many years) exert significant psychological impacts, regardless of whether the radiological release was associated with terrorism or not. However, the fear associated with nuclear or radiological terrorism's intentionality is expected to be associated with particularly high risk perception and profound attendant psychological sequelae (Barnett *et al*., 2006), to an even greater extent than those associated with nonterrorist-related radiological releases (*e.g.*, Bromet, 2014). However, while terrorism is fundamentally a mental health assault on populations and has societal capitulation as a central goal from the perpetrators' perspective, terrorist incidents can have a galvanizing effect on societies, due to a shared sense of outrage (often further spurred by media and political responses). The September 11, 2001 terror attacks on the United States represented such an example. In the short term, these attacks were associated with strong patriotic cohesion, and over the longer term were connected with symbols of defiance against the instigating terrorist incidents (*e.g.*, in construction of the Freedom Tower in New York). Post-terrorism dynamics of social cohesion and defiance could be more pronounced than those following nonterrorism radiological incidents. Moreover, such post-terrorism dynamics may translate into a more intense and aggressive societal emphasis on return to normality, including late-phase optimization efforts, than may be encountered following accidental radiological releases (Barnett *et al.*, 2006).

5.6 Making Decisions

Decisions for the early (or emergency) phase of an incident have to be made quickly, so they are likely to be made directly by elected public officials (or their designees) with limited stakeholder involvement. However, in the recovery and restoration phases, there is ample time for engaging stakeholders in long-term decisions. The transition from the early phase, through the intermediate phase and into the late phase is managed under a traditional National Incident Management System. However, since remediation of a large contaminated area may go on for years, the typical incident command/unified command structure may be augmented to facilitate the inclusion of subject matter experts in a technical working group and stakeholders.

5.6.1 *Regulatory Structure*

In the evolution of a regulatory process, regulations are inherently reactive. Facilities are built, problems are identified, legislators are motivated to address the problems, and a regulatory system is developed. Thus the regulatory structure in place before a major nuclear or radiological incident will not necessarily be relevant to the conditions that exist after the incident has occurred. While some basic regulatory framework may still be useful, there will be a need to quickly evaluate and implement any parameter changes based on shared decision making so that recovery can progress toward agreed upon goals.

For instance, there may be a need to allow air pollution from an emergency generator on a temporary basis, until other sources of electrical power are obtained. There may be a need to establish a transfer station for solid waste before disposal in order to separate the more heavily contaminated waste from lower-level waste that could go into a sanitary landfill. The landfill may have restrictions on taking waste with surface contamination and have radiation detection equipment at the gates to prevent inadvertent disposal of orphan sources. Settings on the portal equipment may need to be adjusted to allow a higher contaminant level to enter the landfill.

As alternative recovery actions are considered, the regulations that may prohibit certain actions may need to be revised in the context of the sustainable conditions after the incident. The regulatory infrastructure should be considered holistically, to ensure that the regulatory net captures the full range of occupational and environmental health and safety concerns and deals with them appropriately. Additionally, the regulatory structure should consider the entire life cycle of the recovery, so that the decommissioning of any temporary facilities and restoration of the site is considered from the very beginning of operation. It is likely that authority will be distributed among many governmental agencies (*e.g.*, environmental permitting in one agency, occupational exposure in another, transportation in another). Close coordination among the governmental agencies is crucial to ensure that there are no gaps in the regulatory structure and that unnecessary redundancy be kept to a minimum.

The regulatory structure is not limited to just granting permits or waiving regulations, it includes adequate resources (financial, human, training and equipment). Regulatory structures are constantly evolving to respond to the needs of communities and workers for health and environmental protection, including social responsibility to under-served populations. In the case of a significant perturbation such as that caused by a major nuclear or radiological incident, there will be a need to accelerate processes to deal with unusual situations. Increasing the pace of regulatory evolution will be a challenge.

Taking advantage of continual improvement through lessons learned, developing performance-based and risk-informed regulations, encouraging the use of best management practices and honoring social responsibility commitments to local communities will require sustained effort by governmental officials.

To the extent that relevant regulatory policies can be identified in the planning stage, thoughtful waiver policies can be developed in advance, providing a framework for decision making.

5.6.2 *Integrating Stakeholders in Decision Making*

Involving stakeholders in decision making is essential for recovery from a major incident. Recent planning efforts by FEMA have considered the concept of the "whole community" with intent to maximize the society's resiliency to address potentially catastrophic consequences.

Stakeholder involvement is an important if not essential component to decision making regarding recovery following a major incident. Following major nuclear or radiological incidents with extensive contamination and consequences, it is necessary that stakeholders involvement be substantial. Recent planning efforts by FEMA against potential IND incidents have considered the concept of the whole community with intent to maximize the society's resiliency to address potentially catastrophic consequences. This approach could potentially lead to a new paradigm of developing self-help programs in order to facilitate the response actions including late-phase activities.

The involvement of the wider community builds trust and credibility. The decisions made though discussions with a wide range of individuals can improve the "buy-in" from various sectors of the community, leading to improved acceptance and sustainability of the final decisions.

Guidance for stakeholder engagement specifically for radiological issues has been provided by HPS (2010), IRPA (2009), and NCRP (2004) (Section 4.4.1.1). These guiding principles were not developed specifically for the purpose of reaching decisions for the return of populations to previously contaminated areas. They are more generic with an aim to promote "the participation of all relevant parties in the process of reaching decisions involving radiological protection, which may impact on the well-being and quality of life of workers and members of the public, and on the environment."

The first step in constructing a process for meaningful stakeholder involvement is acceptance that it will be an evolving process. The area of contamination may have a group of committed stakeholders because of previous (unrelated) circumstances. There may be a core group of involved citizens who are part of an environmental commission, or other type of advisory group. There may be citizens who are acknowledged leaders of public opinion, who are engaged in the community, and who readily step forward to participate. Or, the situation may demand the creation of a whole new group.

There should be a mechanism for continued improvement of the stakeholder process, and for engagement of new stakeholders as a natural progression of involvement occurs. Stakeholders who may have relevance for one aspect of the decision process may lose interest as different considerations arise. The important thing is to keep the process fresh, and to continually respect the values that are expressed.

Stakeholders have responsibility, too. They must be prepared to listen to and learn from diverse viewpoints.

5.6.3 *Approaches to Effective Risk Communication During Late-Phase Recovery*

NA/NRC has defined risk communication as "an interactive process of exchange of information and opinion among individuals, groups, and institutions" (NA/NRC, 1989). Numerous studies have highlighted the importance of effective risk communication in enabling and helping people to:

- understand the risks they face;
- understand how to protect their health, safety, environment, and well-being;
- make informed decisions and choices;
- make the social connections needed to build resilience following a disaster;
- participate in deciding how risks should be managed; and
- see themselves as capable and self-sufficient.

Effective risk communication is challenging in all phases of a nuclear or radiological emergency. However, several unique challenges arise in the latter phases of recovery. A highly sophisticated approach toward risk communication will be required to address the extensive uncertainties involved, understand the complex decisions that need to be made, choose among the large number of policy options available and presented, and successfully negotiate the claims being made by numerous stakeholders.

Effective risk communication in the later phases of recovery has several objectives:

- informing and warning citizens of risks;
- informing citizens of emergency response and recovery plans;
- providing citizens with timely information and instructions to reduce potential injuries, illnesses (physical and mental), casualties, economic losses, and societal disruption, and preventing stigmatization;
- gaining the assistance of citizens in identifying issues of concern; and
- enhancing social cohesion, social resilience, and confidence in risk management authorities.

Risk communication in the latter stages of recovery will directly influence incidents. Poor risk communication will fan emotions and undermine public trust and confidence. In the worst case, poor risk communication will create strife, conflict, and additional crises. Good risk communication can rally support, calm a nervous public, provide needed information, encourage cooperative behaviors, and potentially help save lives. In the aftermath of a major radiological or nuclear incident, effective risk communication can help people feel safe, calm, connected, hopeful, adaptable, cooperative, and become effective problem solvers, capable responders, and self-sufficient, instead of feeling unsafe, anxious, isolated, pessimistic, inflexible, uncooperative, helpless, dependent, fatalistic and victimized.

5.7 Implementing Decisions

Implementing a decision involves careful execution of planned recovery actions along with a number of other actions including documenting the basis and rationale for the decision, communicating the decision to all stakeholders, and providing the procedures for implementing it.

Once decisions have been reached regarding the various recovery actions to be taken, implementation of those actions must be associated with a careful execution of not only planned recovery actions developed in the steps and techniques described above, but also a number of other actions. These other actions include documenting the basis and rationale for the decision, communicating the decision to all stakeholders, and providing the procedures for implementing it. This integration is important because recovery following widespread contamination from a nuclear or radiological incident is likely to be an iterative process that will continue for an extended period of time during which baseline conditions will evolve.

5.7.1 *Transparency of Decision Making*

Transparency in the decision-making process for recovery creates trust between decision makers and stakeholders and results in better-informed decisions being made. Each decision can be particularly important in view of the potential competing priorities and resource constraints that may exist under the incident-induced situation. Transparency provides for the disclosure and communication of basic contextual information to all the stakeholders such as: Who is making the decision? How the decision is being made (*i.e.*, process)? What information is being used in making the decision?

To gain public trust and credibility, the entire decision-making process and resulting recovery plan must maintain transparency throughout late-phase activities. Thus, all decision-making steps need to be properly recorded and disseminated to members of the public through commonly accessible media (such as news or social media). Elements that need to be included are:

- basis for each recovery decision;
- listing of the technologies that will be used and the criteria by which their success will be evaluated; and
- timescale over which this effort applies.

Distinctions will need to be made on which entity (or entities) have the responsibility to implement recovery actions, including those that will be conducted by government, industry, commerce, community, or on a personal level. To achieve the desired level of transparency, easy-to-use, interactive, web-based tools need to be developed that will allow members of the public to view the current situation, and monitor both progress and impact on an area-by-area and pathway-by-pathway basis.

5.7.2 *Effective Communication During Implementation*

> All decisions that are to be implemented must be communicated clearly. Risk communication efforts in the latter stages of recovery must be able to link and align the activities of all sectors (government, private and community). Each sector will have a vital risk communication role to play.

All decisions that are to be implemented must be communicated clearly. This will help enable all individuals who are involved to feel that they have been empowered by the process, and that they are members of the recovery team.

Risk communication efforts in the latter stages of recovery must be able to link and align the activities of all sectors, local, state, tribal and federal governments, the private sector, and voluntary, faith-based and community organizations. Each sector will have a vital risk communication role to play. Existing levels of stress and fatigue will be compounded if organizations offer inconsistent messages conveyed through multiple media by multiple sources. To address this problem, each sector will be required to make effective use of their communication resources and capabilities and use best risk communication practices (Appendix E).

Local authorities and organizations will play a leading role in communicating during the latter phase of recovery. One of the most significant obligations of local authorities and organizations will be to meet the information needs of individuals, families and organizations. Effectively achieving this goal is critical for resilience. Communication for resilience is fundamentally local and social, with a primary goal to encourage positive interactions and relationships between and within communities. In this context, the primary role of the federal government will be to:

- partner and facilitate, particularly in areas of federal jurisdiction or national security; and
- assist, should local authorities and organizations be overwhelmed by the scale of the many challenges they will face.

Leaders will be required to offer clear, consistent, culturally-sensitive, and frequent communications containing critical recovery information, including leadership expectations and guidance regarding roles and responsibilities of individuals and organizations; assistance available to individuals and organizations; and the pace, requirements, and time needed to achieve recovery.

Timely, accurate, credible and clear messages need to be developed regarding various health effects such as the inhalation of resuspended material, the ingestion of contaminated water, and the ingestion of contaminated foods. Ecological concerns must be communicated such as the access controls for humans to contaminated environments. Protective guidelines must be made clear, including, for example, when individuals can return to their homes and to their workplaces. Finally, messages about infrastructure such as when various facilities can be accessed must be clear and timely.

5.7.2.1 *Delivery Channels*. The information needs of stakeholders in the latter stages of recovery will be extensive. It is therefore critical that every available communication method and outlet be maximally and effectively utilized to disseminate and share information. There will be a need to use both traditional media outlets (*e.g.*, television, radio, online news sources) supplemented by strategic use of other delivery channels such as social media (Section 5.7.2.2).

Enhanced, comprehensive and accessible communication networks will create additional channels for agencies and organizations to rapidly deliver critical information. They will also help individuals and communities in the latter stages of recovery to:

- obtain and confirm information through multiple sources;
- obtain and confirm information from those perceived to be trusted or similar to themselves; and
- provide feedback to leaders regarding individual and community needs and expectations.

5.7.2.2 *Use of Social Media*. Social media provide a new, pervasive and potentially valuable means for assisting late-phase recovery from major nuclear or radiological incidents. Social media provide people with enhanced ways to converse, engage in dialogue, build relationships, listen to the views of others, get messages quickly to others, and witness or participate in ongoing discussions and debates.

Over the past decade, there has been an incredible increase in the use of hand-held communication devices by individuals for information sharing. For example, community members recovering from the 2007 Southern California wildfires used social media available through mobile communication devices to stay in contact with friends and family, to search websites advertised in traditional media, to read blog postings, to participate in web forums, and to share photos. Community members also used social media to get local information not provided by traditional print and broadcast media.

Social media relevant to late-phase recovery from a major nuclear or radiological incident include, but are not limited to, the following:

- micro-media/blogs such as Twitter® (San Francisco, California);
- social networks such as Facebook® (Menlo Park, California);
- niche networks such as LinkedIn® (Mountain View, California);
- video services such as YouTube® (San Bruno, California);
- blogs (self-published diary or commentary on a particular topic that may allow visitors to post responses, reactions, or comments);
- wikis such as Wikipedia® (San Francisco, California); and
- picture sharing sites such as Flickr® (San Francisco, California), Picasa® (Google, Mountain View, California), and Instagram® (San Francisco, California).

Challenges to the effective use of social media for information sharing in the late phases of recovery include technical challenges, security concerns, system overloads, and access.

5.7.3 *Program of Implementation*

The recovery plan documents the essential information for understanding the rationale for the decisions including the prioritization of areas for recovery actions and the information and resources available at the time of the decision. It lays out the statements of work to be conducted, the contracting procedure or other relevant mechanisms that will be used to initiate the recovery actions, and the timescales over which they will be implemented. The responsibility for management and oversight of the recovery plan also needs to be articulated. Although the next main step in the recovery process is to monitor and evaluate the overall success of the recovery plan (Section 5.8), it is important that the plan be sufficiently flexible to allow immediate adjustments and improvements during the implementation phase. The importance of recording and communicating such findings and changes cannot be underestimated both in terms of ensuring the accuracy of the collective knowledge and data used to make recovery decisions, and the transparency of the process.

Implementation of the optimization process will necessarily be incident and site specific. Thus, it is difficult to generalize the approach for every incident due to the extreme complexity involving every step of the decision making for late-phase recovery. Such differences have been fully illustrated by the major nuclear or radiological incidents discussed in Section 3. Consequently, the aforementioned principles and methods are meant to serve as general guidance to address the relevant issues that would be encountered in late-phase situations. Practical applications are provided in Appendix F to clarify further some of the important parameters and considerations.

5.8 Monitor and Evaluate

One of the key goals of a long-term recovery program is to reduce the risk from chronic exposure to environmental contamination and to restore, to the extent possible, a sense of normalcy to the affected population. This goal includes not only a reduction in the risks associated with exposure to radiation but also the psychological burden resulting from the disruption of people's lives due to contamination, relocation and loss of property and livelihood as well as the fear of the future consequences of radiation exposure. A long-term monitoring program is a key element in the overall recovery program.

Long-term monitoring might include the direct surveillance of individual health conditions within the affected area. Another key part of a long-term monitoring program is an assessment of food and water, as well as the environment in general. Additionally, a long-term monitoring program might assess various economic indicators relevant to the goals decided upon through the optimization process. More detailed discussions on long-term monitoring are provided in Section 6.

6. Long-Term Management of Radioactive Contamination

6.1 Introduction

The optimization process is an iterative approach to remediation; therefore it is important to develop a long-term management strategy that includes monitoring of contamination levels.

The widespread and highly variable nature of radioactive contamination from a major nuclear or radiological incident requires prioritization of the remediation effort. Even after some remediation activities have been completed, residual contamination may remain. Because the optimization process involves an iterative approach to remediation, it is important to develop a long-term management strategy that includes monitoring of contamination levels. Both during and after cleanup activities, a robust monitoring program is critical to sustaining the recovery, health, and wellbeing of the community. A variety of management techniques will be needed, especially in situations where there are large variations in contamination. This section outlines the considerations for a successful long-term monitoring program and for managing areas with residual contamination.

6.2 Long-Term Monitoring

Long-term monitoring supports the optimization process by assessing whether remediation goals set by the authorities and stakeholders have been met and whether improvements need to be considered.

A long-term monitoring program tracks both the progress of remediation activities and the impact of residual activity levels of radionuclides on health and the environment, including food, water and biota. A long-term monitoring program also assesses the impact of the residual activity levels on industry, infrastructure, residential and commercial real estate, and public lands. As such, the monitoring program must account for all routes of exposure and potential intake. Monitoring includes measurements of surface contamination (both fixed and removable), ambient exposure rates, areal and volumetric contamination in various media (soil, water, vegetation, food) and biological samples to assess potential doses to humans, animals, and the environment.

Long-term monitoring is also important to assess and track the overall health of individuals in the affected areas beyond their exposure to radiation. In addition to accounting for the physical and psychological trauma from real or perceived radiation exposure or injury to self and/or family, long-term monitoring considers other contaminants created by the incident as well as the psychological trauma from illness or injury, displacement, loss of property, loss of livelihood, loss of security, and perhaps loss of family, friends and/or acquaintances. Registries will be an important component of the long-term monitoring program for ensuring that the needs of the affected population are being met by the healthcare system over an extended period of time. The process will be complicated by relocation and loss of previous health records.

Long-term monitoring supports the optimization process by assessing whether remediation goals set by the authorities and stakeholders have been met or whether improvements need to be considered. Monitoring helps to evaluate the feasibility and success of any previously untested interventions and provides feedback to authorities so that strategies might be adjusted as necessary. Monitoring data can also support the need for additional resources for remediation. Similarly, adjustments may be needed in the monitoring program itself based on the results of recovery activities (Section 5.8).

It is important to communicate regularly with stakeholders and members of the public, both directly and through the media, about the progress of remediation activities. The results of monitoring should be periodically reported and placed in context with the established goals. Officials should also report on the results of health and risk assessments and the need, if any, to make changes in the monitoring plan. Likewise, members of the public will need to provide input to decision makers to prioritize monitoring activities and may participate directly in monitoring as part of a self-help plan (Section 5.6.2).

While the final goal of remediation is the reduction and stabilization of the activity of radionuclides in the environment to an acceptable level, monitoring will likely need to continue beyond this endpoint to verify that the planned conditions have been achieved and maintained and that risks to individuals have decreased or become stable over time.

6.3 Timeframe

Incident-specific planning for long-term monitoring should begin as soon as authorities have developed a reasonable assessment of the magnitude of the incident.

A long-term monitoring plan is specific to the incident and can only be developed after the incident has occurred. However, significant planning can and should take place beforehand as part of a comprehensive preparedness program. During this period authorities should assess available resources to establish baseline capabilities. By using a scenario-based approach, planners can project the needs for an incident of a given magnitude and determine the requirements for additional resources. For large-scale nuclear or radiological incidents, surge requirements may need to be provided by external partners. These relationships should be developed in the pre-incident timeframe and necessary written agreements identified (*e.g.*, regional compacts, memoranda of understanding).

Incident-specific planning for long-term monitoring should begin as soon as authorities have a reasonable assessment of the magnitude of the incident and availability of the resources that will be required to carry out monitoring activities. During the intermediate phase, resources should be marshaled and agreements and commitments for these resources should be finalized. Monitoring and sampling plans should also be finalized during this period by the responsible organization(s). Because there might be a formal transition of authority when the response moves from characterization to cleanup to recovery, all important legal documents or contracts should be completed during the intermediate phase.

It is generally considered that the intermediate phase ends and long-term recovery begins after the extent and nature of the contamination has been adequately characterized. However, since the overall recovery is a continuous process (Section 3), the preparedness effort could start much earlier.

The characterization phase will define the geographic boundaries and magnitude of the contamination. Characterization typically lasts from weeks to months depending on the nature of the incident. The monitoring requirements usually diminish over time as the community moves through cleanup to recovery and ultimately to the optimized recovery goals. However, late-phase monitoring will likely continue beyond the point where contamination is considered to be stabilized, in order to ensure that the cleanup has been optimized and to monitor any residual hot spots or redistributed contamination.

The duration of the long-term monitoring program will be a function of the recovery goals established by public officials and stakeholders, the data quality objectives required to meet cleanup targets, and the resources that are committed to recovery operations. Decisions regarding future use of contaminated lands will play a significant role in determining when monitoring may be reduced or stopped altogether. Alternative land uses that tolerate higher residual contamination levels and application of recovery options that lead to the condemnation of certain properties could shorten the recovery period and lessen the need for monitoring. However, these options need to be considered against other potential negative impacts on the community (such as the loss of economic capability) and on the environment (such as disruptions to normal ecological functioning) (Copplestone *et al.*, 2001; IAEA, 2006b).

6.4 Health Monitoring

Long-term health monitoring will play an important role in assessing the physical and psychological damage from a major nuclear or radiological incident.

The major goal of remediation is to reduce the potential for adverse health effects from chronic radiation exposure. However, as victims of a terrorist attack or a severe nuclear accident, the affected population is also likely to have been psychologically traumatized and need mental health surveillance and treatment. Long-term health monitoring will play an important role in assessing the physical and psychological damage from a major nuclear or radiological incident. Health monitoring will continue to be a resource-intensive endeavor well into the future.

To assess the full physical impacts from a major radiological or nuclear incident resulting in widespread contamination, the monitoring plan must consider all potential exposure pathways. While short-term exposures and potential effects are dominated by surface contamination, longer-term consequences need to include the incorporation of radionuclides into the food chain, including crops grown in planting cycles, forage by grazing animals and game, and groundwater contamination. Surface contamination may continue to be an issue of concern if there is a potential for resuspension of radioactive material and inhalation exposure. The details of risk and dose assessment are discussed in Section 5 and in Appendix F.

6.4.1 *Monitoring Considerations*

During the early phase of an incident, screening methods will be needed to monitor exposed and potentially-exposed individuals and take medical interventions as needed to avoid or mitigate the potential for severe tissue reaction (previously called deterministic) effects (NCRP, 2008a). Due to the large number of people who may require screening, it may be necessary to impose triage methods such as setting somewhat higher screening criteria than desired to increase throughput and serve the widest population. Further, because of technical limitations and relatively high background levels, it may not be possible to detect contamination by alpha-particle-emitting radionuclides. Finally, due to limited capacity to perform certain types of assays on a large scale, it may be necessary to set a higher screening threshold for dose to ensure that care is provided to the most seriously injured people (CDC, 2005; EOP, 2009).

By the late phase, most cases of tissue reaction effects should have been identified and the vast majority of people should have been effectively decontaminated or found not to have been exposed at all. Thus, the number of people requiring long-term follow-up should be significantly reduced. This reduction will allow for a more thorough assessment of each individual using more sensitive monitoring and/or biodosimetry assays. Whereas screening for acute radiation syndrome in the early stages after an IND might have required a predicted dose threshold of 1 to 2 Gy absorbed dose where mild acute radiation syndrome effects might be anticipated (Mettler *et al*., 2007), late-phase monitoring may include individuals who received lower doses. Long-term monitoring for lower-exposed individuals will be focused on potential stochastic effects (*i.e*., cancers) and the results from these monitoring activities may support epidemiologic studies (Bouville *et al*., 2014). With reduced numbers of potentially-affected individuals and less pressure to address immediate health issues, investigators and healthcare providers may be able to perform more sensitive assays. As with other elements of the recovery program, the thoroughness, sensitivity and specificity of long-term monitoring will depend greatly on available resources.

A variety of clinical and radiological assessments may be needed to monitor the exposed population over the long term. Concern will have shifted to those individuals with significant intakes of long-lived radionuclides or very high (but sublethal) external exposures who are faced with radiation-related delayed effects such as cancer. Persons with high intakes of radionuclides will need to be routinely monitored by an appropriate bioassay method to assess the clearance of radionuclides from their bodies and make individual organ dose estimates. Persons with high exposures to external radiation will need to be followed with a range of clinical examinations to assess current and future changes in health status. Health examinations may include tests of hematological status, endocrine function, immunocompetence, pulmonary function, and electrolyte balance, as well as general well-being.

There may be an interest in conducting epidemiologic studies in conjunction with health monitoring, especially if estimated population exposures are sufficiently high to enable quantification of dose-response relationships.

The goals of epidemiologic studies are to:

- identify health conditions in exposed individuals in comparison with those in nonexposed or minimally exposed individuals;
- assess whether there is a statistically-significant excess risk, recognizing that the power of an epidemiologic study is determined by the doses received by the exposed population, the size of the exposed population, the background incidence of the disease or conditions under study, and the influence of confounding factors; and
- provide information to improve current estimates of risk (WHO, 2011).

Depending on the nature and magnitude of the nuclear or radiological incident, a subpopulation of individuals may have received doses high enough to warrant medical countermeasures to treat or mitigate the potential health effects. For example, in cases of high intakes of ^{137}Cs or transuranic radionuclides, various blocking or chelating agents may be administered to increase the elimination rate of these radionuclides from the body and so reduce the internal dose. To assess the efficacy of the treatment, individuals should be monitored for residual activity and excreted activity by either direct (whole-body counting/imaging) or indirect (urine and/or fecal analyses) methods, or both. An assessment of residual activity and the resulting committed dose is critical in deciding when to stop treatment. In an extreme situation where persons received a high enough external dose (*i.e.*, from an IND detonation) to induce acute radiation sickness, treatment with biological response modifiers (cytokines) might be attempted to reconstitute the hematopoietic system (RITN, 2014). In these cases, individuals would need to be followed with a series of clinical laboratory tests (*e.g.*, peripheral lymphocyte counts) in addition to any radiological assessments made for intakes of radioactive materials. Such individuals will likely be treated in an inpatient hospital setting.

6.4.2 *Psychological Assessment*

Radiation exposure from accidents or malevolent incidents will have severe psychological impacts on the victims. This section addresses the potential impacts and the types of assessments and interventions that may be required in the affected population.

Incidents involving radiation exert powerful psychological impacts on populations because of the considerable fear that radiation imparts. Seminal research on risk perception has identified two relevant clusters of fear-related factors for a given hazardous agent: "threat," which includes such risk characteristics as potentially fatal, uncontrollable, and bearing adverse outcomes that are difficult to mitigate; and "observability," which includes delayed effects and inability to directly sense exposure (Slovic, 1987). Agents associated with high "threat" and low "observability" levels evoke a heightened degree of fear (Slovic, 1987). Radiation exposure aligns with this "high threat/low observability" profile because: radiation is physically imperceptible to the human senses and requires sophisticated monitoring equipment for detection, radiation is a known carcinogen, cancer is generally a feared disease and often associated with death, radiogenic cancers have long latent periods (measured in years if not decades) creating a high uncertainty in when and how cancer will present, a population's exposure to radiation from a terrorist act or a radiological or nuclear incident is involuntary, and exposures large enough to cause acute radiation sickness are potentially fatal (Barnett *et al.*, 2006).

The mental health consequences for those affected by a major nuclear or radiological incident include direct psychological sequelae and indirect effects such as anxiety, demoralization, fear, terror and isolation due to stigma. Social stigma attached to victims of radiation goes back to the aftermath of the wartime atomic bombings of Hiroshima and Nagasaki, when men could not find work and women were unable to marry due to fears they were "tainted." This phenomenon constitutes "psychological contagion," (*i.e.*, the spreading of an emotional or mental state among people) a phenomenon found to be important in populations exposed to terrorist acts (Barnett *et al.*, 2006; Saathoff and Everly, 2002). Research suggests that following an act of terrorism, the number of psychological casualties can be expected to far exceed that of the physical casualties (Barnett *et al.*, 2006; DiGiovanni, 1999; Holloway *et al.*, 1997; NA/IOM, 2003).

Psychosocial sequelae can manifest in a broad spectrum of outcomes that vary according to the nature and intensity of the incident. Such mental and behavioral health effects range from sleep disturbance, anxiety, and anger, to post-traumatic stress disorder and depression. The Institute of Medicine anticipates an estimated four psychological casualties for each physical casualty, a ratio observed in recent terrorist attacks (NA/IOM, 2003). However, for most individuals, post-terrorism mental health outcomes will not result in significant psychopathology (Bass *et al.*, 2005). To this end, a different ratio might be expected depending on the type of exposure scenario (*e.g.*, the ratio for an IND attack might be higher than for the explosion of an RDD due to differences in the severity of the destructive impact).

A major nuclear or radiological incident may compromise individual and societal support systems, which in turn can contribute to diagnosable psychiatric illness including post-traumatic stress disorder and depression. Some of these adverse sequelae may not develop for a long time after the incident.

Professionals who are called upon to respond to an act of nuclear or radiological terrorism are also vulnerable to long-term mental health consequences (Bass *et al.*, 2005). In addition to first responders and emergency workers, other populations vulnerable to the psychological consequences of terrorism include the elderly, families with children, rural residents, and those with pre-existing chronic mental illness. These groups are at risk because they may already be encountering medical, psychosocial and/or financial difficulties that would be worsened by a major terrorist act or nuclear or radiological incident.

Many of the psychosocial challenges faced by long-term restoration-phase efforts will be exacerbated by recognized gaps in surge capacity within the public mental health system (NA/IOM, 2003). Given these anticipated impacts and attendant systemic challenges, robust pre-incident planning for long-term restoration-phase delivery of mental health services must be an essential element of preparedness for major radiological and nuclear incidents at all jurisdictional levels. Such planning should involve training of nonmental health professionals in psychological first aid (Everly *et al.*, 2010). To augment mental health surge capacity, psychological first aid facilities could be established to provide efficient identification and triage of those at risk for longer-term adverse mental health outcomes. Additionally, longer-term psychosocial/behavioral impacts should be monitored through federally coordinated active surveillance systems.

While the Fukushima Dai-ichi NPP disaster is too recent to gauge long-term mental health adverse impacts, there are preliminary indications that mental health and psychological issues are becoming a significant population concern.

Mental health problems presumably associated with the fear of radiation are gaining recognition as a serious consequence of exposure, even when the associated dose is tiny and of no discernible future health consequence (Bromet, 2014). Mental health and lifestyle surveys of several hundred thousand residents of Fukushima prefecture have revealed substantial numbers of mental health disorders requiring medical care (Yasumura *et al.*, 2012).

News articles have reported anecdotal but informative stories of mental anxiety and behavior effects among Fukushima prefecture residents. For example, an article in *The Guardian* newspaper (Haworth, 2013) painted a sobering picture of discrimination, stigmatization and adverse behavior changes:

> "Tales exist of people from Fukushima being barred from giving blood, having their car windows smashed or being asked to provide a medical certificate of their caesium levels on job applications.
>
> "A Tokyo maternity hospital advised a new mother not to let her Fukushima-based parents visit their new grandchild, 'just to be safe'. Prejudice against women is the most pervasive: many negative comments in the media and on websites insinuate that Fukushima women are 'damaged goods'. Even some people who are supposedly on the side of radiation victims are prepared to throw them on the reproductive scrap heap.
>
> "Last year, prominent anti-nuclear activist Hobun Ikeya, the head of the Ecosystem Conservation Society of Japan, said at a public meeting: 'People from Fukushima should not marry because the deformity rate of their babies will skyrocket'.
>
> "The stress on family life for all two million people across Fukushima has been immense. Marital discord has become so widespread that the phenomenon of couples breaking up has a name: genpatsu rikon or 'atomic divorce'.
>
> "There are no statistics yet, but Noriko Kubota, a professor of clinical psychology at the local Iwaki Meisei University, confirms there are many cases. 'People are living with constant low-level anxiety. They don't have the emotional strength to mend their relationships when cracks appear,' she explains. Couples are being torn apart over such issues as whether to stay in the area or leave, what to believe about the dangers of radiation, whether it is safe to get pregnant and the best methods to protect children. 'When people disagree over such sensitive matters, there's often no middle way,' adds Kubota, who also runs a counselling service.
>
> "Moreover, now that what Kubota calls the 'disaster honeymoon period' of people uniting to help each other in the

> immediate aftermath is over, long-term psychological trauma is setting in. ‘We are starting to see more cases of suicide, depression, alcoholism, gambling and domestic violence across the area,’ says the psychologist. The young are not immune either. In late 2012, Fukushima's children topped Japan's obesity rankings for the first time due to apparent comfort eating and inordinate amounts of time spent indoors avoiding contamination. ‘From the point of view of mental health, this is a very critical time,’ says Kubota.”

Chernobyl mental health research is beginning to reveal long-lasting population mental disorders following the nuclear accident (Bromet *et al*., 2011). Chernobyl emergency responders and cleanup workers were found to have elevated rates of post-traumatic stress disorder and depression two decades after the nuclear reactor accident (Bromet *et al*., 2011). General population studies have also indicated heightened rates of subclinical and clinical depression, anxiety, and post-traumatic stress disorder at two decades post-Chernobyl (Bromet *et al*., 2011). While the literature is inconclusive regarding the extent of Chernobyl’s psychological effects on children who were prenatally or otherwise exposed, it is apparent that the mothers of young children exposed to this incident have remained a high-risk population for depression, anxiety, and post-traumatic stress due to their ongoing concerns about their families’ health (Bromet *et al*., 2011). Relevant psychosocial stressors following the Chernobyl nuclear reactor accident included the trauma of sudden displacement, challenges of being a long-term refugee, interference with social networks, and illness (Barnett, 2007). Additionally, a mental health study on Russian immigrants to the United States conducted 15 y post-Chernobyl found that greater proximity to Chernobyl at the time of the reactor accident in 1986 was associated with higher levels of long-term anxiety and post-traumatic reactions than living at farther distances (Foster, 2002). This relationship between initial physical proximity to the Chernobyl nuclear reactor accident and degree of long-term mental health outcomes was also reported among Russian immigrants to Israel (Remennick, 2002) and Russians who remained in the former Soviet Union (Havenaar *et al*., 1997).

6.4.3 *Registries*

To conduct adequate health assessments in populations affected by major nuclear or radiological incidents, it is important to develop and maintain a registry of the radiation-exposed population with adequate demographic and baseline medical information to allow for long-term follow-up. It will be even more important to have the basic elements and structure of such a registry planned in advance so that data collection and database entry can begin immediately, as the population is likely to disperse over time.

Local communities need to be self-sustaining for at least 48 h following a nuclear or radiological incident (NCRP, 2010b). This is also the period when a registry should be created for long-term monitoring. Therefore, in the acute aftermath of a terrorist RDD or IND attack or a major nuclear or radiological incident, local response agencies should immediately take a lead role in establishing registries for future population monitoring. In this local context, community-based reception centers would be important venues for a broad array of local response activities, including registry enrollment (NCRP, 2010a). Like other aspects related to registry formation, identifying and establishing these community-based centers requires detailed pre-incident planning by local jurisdictions (NCRP, 2010a). Alternate-site identification will be vital for ensuring redundancy and resiliency in case of damage or destruction to these centers.

Depending on baseline local resource availability and the potential physical impacts of the incident on a community's public health and healthcare infrastructure, even a small number of affected individuals could rapidly outstrip local surge capacity to deal with healthcare issues (NCRP, 2010b). Healthcare infrastructure surge capacity limitations have been well documented (NA/IOM, 2007), and have direct implications for screening and registry creation efforts. Against this backdrop, community planning for registry enrollment processes must account for potential gradations in the scale of affected populations, and minimize the amount of initial registry information collected to the extent possible (NCRP, 2010b).

Local efforts at registry development would require federal public health support and coordination (NCRP, 2010a) as soon as possible following a major nuclear or radiological incident. Depending on the incident's type and scale, long-term registry maintenance can be a highly complex and resource-intensive process. Previous nuclear or radiological incidents have provided insights on registry development. For example, harmonizing diagnostic criteria and data-management processes was identified as a challenge for developing respective population-based tumor registries in Hiroshima and Nagasaki (Mabuchi, 1990).

In a registry context, active methods of long-term follow-up (*e.g.*, contacting enrolled cohorts by mail or telephone) are sometimes preferable to passive forms (*e.g.*, using cancer registry records to assess cancer incidence) (NCRP, 2010b), although interpretation of active method results can be hampered by high nonresponse rates, response bias, and death before contact is made. Outmigration presents a significant barrier to active follow-up and needs to be factored into current registry planning efforts. In the case of Hiroshima and Nagasaki, for example, as of 1990 approximately 20 % of surviving Life Span Study cohort members no longer resided in areas bounded by the tumor registries, with migration rates being inversely related to age at exposure (Mabuchi, 1990), which suggests that the percentage of Life Span Study residents in the tumor catchment areas has likely decreased over the past two decades. Addressing these outmigration-related issues is challenging, requiring intensive coordination between federal, state and local public health and stakeholder agencies; sustained cohort tracking efforts; and improved statistical analytic approaches to adjust if possible for migratory movement in cancer incidence studies (Mabuchi, 1990).

6.4.4 *Resource Requirements and Infrastructure Needs*

Long-term health monitoring is a complex and resource-intensive enterprise. Due to migration and resettlement of displaced populations, the responsibility for monitoring may shift to otherwise unaffected regions.

An historical example may provide a useful context: the aftermath of the Chernobyl nuclear reactor accident highlighted the logistical complexity of long-term monitoring (IAEA, 2006a). In the 20 y following Chernobyl, millions of samples were collected and analyzed and monitoring procedures conducted to assess and model internal doses from intakes of radionuclides (IAEA, 2006b).

Following a major nuclear or radiological incident, longitudinal resource challenges will begin immediately, given the likelihood of rapid evacuation of persons potentially exposed. This time-sensitive challenge is compounded in the United States by recognized limitations in the nation's post-disaster surge capacity (NA/IOM, 2007). Consequently, early post-incident exposure registry activities that pave the way for longer-term monitoring have to be made as efficient as possible. In the immediate aftermath of a nuclear or radiological incident, this requisite efficiency limits the amount of tracking information collected to only the essential details required for initial monitoring and longer-term follow-up.

The scale of the incident will dictate the logistical complexity, resource intensity, and nature of long-term monitoring efforts. For example, in the case of an RDD that causes only very low-level exposures, the resource intensity of long-term monitoring may be relatively greater for mental and behavioral conditions rather than for physical aspects. Moreover, the complexity and resource reliance of long-term monitoring will depend heavily on the immediate and longer-term health infrastructure damage to directly affected communities, the number and geographic distribution of individuals exposed, the immediate incident-specific dynamics and pace of evacuation, and long-term outmigration and resettlement patterns.

Given these challenging variables, planning for major nuclear and radiological incidents must take into account the range of potential resources and infrastructure required to carry out long-term monitoring. All sectors of society including government laboratories, public and private hospitals/laboratories, and universities will likely need to contribute resources. Cross-training of public health and healthcare workers to include long-term monitoring activities may be considered. Laboratories may need to develop cross-capabilities that fall outside of normal activities, and a monitoring network should be considered to manage workflow and ensure consistency at all jurisdictional levels.

6.5 Food and Other Commodities

Following a terrorist attack with an RDD or IND or a major NPP incident, there is the potential for a wide variety of commodities to become contaminated. While food and water might be the products of highest initial concern, virtually all classes of goods and property are vulnerable to both the contamination incident itself and the redistribution of radionuclides over time. Contamination could include critical infrastructure needed to maintain the health, safety and viability of the community during its time of greatest need. There might also be a need to monitor resources to assist individuals to make personal decisions about consumption, as the government may be able to control commerce but not personal behavior (self-help). Although guidance does exist for managing radioactive contamination during the normal operations of regulated nuclear and radiation activities, there is little guidance available for widespread contamination following incidents such as from RDD or IND terrorist attacks.

This section covers approaches to controlling foodstuffs, other commodities, infrastructures, and property and discusses the need for long-term monitoring to help make decisions about current and future land uses.

6.5.1 *Food, Water and Agriculture*

6.5.1.1 *Food*. The principal means of controlling food potentially contaminated with radionuclides from a nuclear or radiological incident is through the use of intervention levels based on the activity concentrations in food (typically in Bq kg^{-1}). These intervention levels are derived from a target dose referred to as the PAG. In the United States, FDA published revised derived intervention levels in 1998 (FDA, 1998; 2004), based on a PAG of 5 mSv committed effective dose equivalent or 50 mSv committed dose equivalent to any organ or tissue (FDA, 2004). Internationally, the most commonly used intervention levels are provided by the Codex Alimentarius Commission (Codex, 2012). This group has provided guidance levels that are also in units of Bq kg^{-1}, but are derived from a PAG of 1 mSv y^{-1} committed effective dose equivalent. While there are several differences in the underlying assumptions behind these derived levels and the final values of the levels, the official guidance used in the United States and internationally are similar in levels of protection provided and risk tolerance considered.

In the recent case of Japan following the Fukushima Dai-ichi NPP accident, government officials used a slightly different approach to deriving intervention levels, but again arrived at guidance levels comparable to those of the United States and Codex Alimentarius Commission (WHO, 2012). It should be understood that these levels are generally based on conservative assumptions in order to provide a high level of protection in the early phase following an incident until such time that a more detailed analysis can be conducted. Then, based on the specific circumstances of the incident, it may be possible to relax the criteria for entry into the food supply or it may be found necessary to tighten the controls. It may also be necessary to make adjustments for special subpopulations with particular dietary requirements (*e.g.*, children, groups with cultural dietary restrictions, the sick, and elderly).

Most published guidance supports the position that decisions about restricting food should only be made on the basis of definitive measurements and well-defined intervention levels (ICRP, 2009). Because of the high stakes involved in restricting the use of food, including the loss of income to farmers and the loss of confidence by the populace for the overall quality of the food supply, governments should be exceedingly cautious about using arbitrary criteria for restrictions or otherwise deviating from published national and international guidance. The setting of guidance levels requires that the affected jurisdictions have adequate monitoring and analytical capability to accommodate the large number of samples that result from a major nuclear or radiological incident. In the aftermath of the Chernobyl nuclear reactor accident of 1986, roughly 12,000 people in 1991 to 1992 were employed in 73 agricultural laboratories and 749 veterinary laboratories in the former Soviet Union (IAEA, 2012). It may be prudent and necessary to form and use a network of laboratories and sampling teams from outside of the affected region to provide surge capacity and analytical facilities in a lower radiation background environment. Depending on the specific circumstances of the nuclear or radiological incident, there is the potential for contamination to be spread over a wide area and for a very large number of samples to be generated. Since it is likely that there will not be sufficient resources to monitor all products, it is important to develop a rigorous, statistically valid sampling and analysis plan to maximize resources, ensure the highest quality of results, and instill confidence in consumers. All laboratories need to follow the same protocols to guarantee the comparability and reliability of results. U.S. governmental organizations such as the DOE National Nuclear Security Administration (*i.e.*, FRMAC) have been working to resolve this problem and have developed and exercised guidance for monitoring, sampling, and dose assessment (FRMAC, 2007) that can serve as guides for future incidents. To the extent possible, local communities should be trained in basic monitoring techniques so that they can assess those portions of the food supply that fall outside of government control (*i.e.*, home gardens) as a way of regaining control of their situation and developing a sense of community resilience.

Although most countries have criteria for restricting contaminated food from commerce in the immediate aftermath of a radiological incident, there is not universal guidance on the management of long-term contamination of the food supply from long-lived radionuclides. While there may be an intrinsic assumption that the activity concentrations in food will decrease with time or that all contaminated products will be completely removed from the food supply, these assumptions may not hold for all situations, and will depend on the nature of the incident and the specific circumstances of the affected areas.

In certain cases, government officials and stakeholders may conclude that it is necessary or important to allow a certain amount of product with increased levels of radioactive content into the food supply to meet dietary needs or to support a sector of the economy. Stakeholders should consider whether there will be widespread acceptance of the foodstuff in commerce. This becomes especially important if the foodstuff is exported to an uncontaminated region. Nevertheless, the goal should be to reduce dose from exposure to radiation through the food supply under the ALARA principle. Such reduction in dose may require iterative analyses of the exposure potentials and an adjustment to intervention levels.

Recent experiences in Japan following the Fukushima Dai-ichi NPP incident and experiences following the Chernobyl nuclear reactor accident illustrate the pitfalls in changing the acceptance criteria for the radioactive content of food (IAEA, 2006a; WHO, 2012). Federal and state agencies should be cautious in changing intervention criteria too abruptly as such changes might raise questions about the safety of previous and revised levels, create confusion, undermine the confidence of consumers, and create distrust among those affected. Furthermore, entities outside of the responsible parties should refrain from using alternate criteria for other than protective measures as this will also create confusion and distrust in the minds of members of the public. Abrupt changes in criteria may have negative consequences that affect the confidence of consumers and also have significant implications for regional and international trade (ICRP, 2009).

It is important to realize that as acceptance criteria change, so do the requirements for monitoring and analysis. As recently observed in Japan, the lowering of guideline levels to achieve a lower projected effective dose from 5 to 1 mSv y^{-1} results in longer counting times and the need to use more sensitive measurement equipment. If it was sufficient in the past to use a survey meter for screening samples, it may now be necessary to conduct a full laboratory analysis under a more rigorous protocol. Given the limitations on resources and other societal objectives, the decision to make changes in intervention levels must be optimized and should include stakeholder involvement.

6.5.1.2 *Water.* A number of options have been considered over the years for emergency guidelines related to drinking water. Water guidance is partially addressed in the FDA food PAGs as a component of food as prepared for consumption and as a beverage (tap water) (FDA, 1998). A similar approach was taken by international organizations (CEC, 1987; 1989; Codex, 2012). U.S. food guidelines currently apply to consumption in the first year after an unintentional release of radionuclides. Current U.S. policy for radioactive contamination in drinking water, including accidental or intentional incidents, defers to the statutes of the Safe Drinking Water Act for both emergency and long-term management of drinking water supplies. Separately, WHO has set guideline levels specifically for drinking water at 10 Bq L^{-1} for ^{90}Sr, ^{131}I, and ^{137}Cs (WHO, 2011).

Monitoring requirements for water are based largely on three categories of risk: the potential for radioactive contamination to enter the drinking supply, the potential for contamination to be transferred to agricultural products through root uptake, and the transfer of radionuclides to fish and other marine animals. Of these three categories, the area of greatest concern relates to the potential for uptake into fish and marine animals. However, based on the experience from Chernobyl, the issue of contamination in water is most important in the early period following a release of radioactive material into the environment, and the level of contamination decreases significantly with time (IAEA, 2006b). In particular, long-term contamination in surface water is very low, especially in open systems due to sedimentation and a high degree of "flow through." Closed systems (*i.e.*, lakes) may present a long-term source of contamination for uptake into fish, requiring more intensive monitoring. Some data collected in Europe following the Chernobyl nuclear reactor accident suggested the potential for "soil fixation" to be reversible (Smith *et al.*, 2000). Elevated levels of ^{137}Cs found recently in fish from the waters off the coast of Fukushima, Japan, suggest that certain ecosystems may be susceptible to redistribution of contamination and continued uptake into some species (Buesseler, 2012). Thus, the need for monitoring should take into account local variations in the biochemistry of the environment.

The long-term risk from contamination in groundwater is exceedingly low relative to other potential sources of exposure such as groundshine and ingestion of contaminated food. Most likely forms of radionuclides, including strontium and cesium, percolate very slowly through soils such that only very small quantities are ever likely to enter groundwater. Other results from Chernobyl showed that irrigation with surface waters did not contribute significantly to plant uptake or human exposure. However, early flooding after the reactor accident did spread contamination to some areas that had not previously been affected by the radioactive releases (IAEA, 2006b).

Overall, the monitoring requirements for water should significantly decrease over time and may eventually be limited to closed systems. It is likely that exposure through the aquatic pathway will be a small fraction of the total dose to humans.

6.5.1.3 *Projected Changes in Uses of Agricultural and Pasture Lands*. By the time long-term monitoring begins, most decisions will have been made regarding the fate of agricultural products that were growing and/or harvested during the nuclear or radiological incident and continuing through the plume phase. However, after plume passage, long-lived residual activity will redistribute throughout the environment and enter the soil leading to the potential for uptake in crops and pastures in subsequent years. Therefore, decisions will need to be made concerning the future uses of agricultural and pasture lands. Modeling, informed by sampling, will be required to answer questions of land use. Methods have been developed to derive response levels based on measurements of radiation or radionuclides in soils that would lead to a crop contaminated at the derived intervention level (DHS, 2008a; Yu *et al*., 2009). This method was described by Yu and colleagues in the context of rice planting in Japan following the Fukushima disaster (Yu *et al*., 2011). Thus, monitoring will continue to play a vital role in decision making for food management well into the future. Diverting contaminated agricultural land into alternate uses with a lower exposure potential to humans will lower the requirement for monitoring in this context. However, this option should be weighed against the costs associated with the displaced agricultural output.

Other food production systems in forests and park areas may prove to be more difficult to remediate and monitor due to their complex terrain and ecology. Thus, although monitoring will still be important for making decisions about access and use, there is likely to be much less opportunity for remediation in these areas, and population doses will need to be controlled through management techniques as described later in this section. Accordingly, the need for long-term monitoring in forest and park areas will be less extensive, particularly if access is restricted.

6.5.2 *Other Commodities and Critical Infrastructure*

While food and water are the most fundamental areas of concern for most people following a radiological or nuclear incident, the impact on other commodities and infrastructure cannot be overlooked as all aspects of commerce are inextricably bound together. Such interconnectedness was demonstrated most recently following the Fukushima Dai-ichi NPP accident as the effects of the releases were not limited to Japan, but were experienced worldwide. In general, there are few published criteria for addressing contamination in consumer products (IAEA, 1996; ICRP, 1999).

6.5.2.1 *Medical Products*. Medical products represent a critical pool of resources that are needed both in the short- and long-term phases following a nuclear or radiological incident. Monitoring plans and release criteria need to be developed for these products so that they might be salvaged for use and not wasted. These methods and limits should address both surface contamination as well as radionuclide incorporation into the product. These considerations are especially important for parenteral products that are administered systemically to patients. Coordinated regulatory efforts will be required since these medical products fall under the purview of numerous local, state and federal agencies.

6.5.2.2 *Consumer Products*. Depending on the location of a given nuclear or radiological incident, there is the potential to affect numerous manufacturing facilities, warehouses and distribution centers, and with them a significant portion of the local or national economy. Therefore, it will be important to develop plans and criteria for the release of consumer products to sustain the economy, re-establish confidence, and return to "normal" as soon as possible, while ensuring the health and safety of consumers. These plans and criteria also need to include development of methods to assess contamination in shipping conveyances, which present a unique challenge. Typically, personnel responsible for monitoring large containers at ports or other large shipping facilities do not possess equipment that can accurately assess contamination or radiation levels inside a container. To do so requires back-up support from laboratories with sophisticated equipment and additional resources to conduct more detailed inspections on containers that register above background on survey meters or alarming dosimeters.

6.5.2.3 *Industrial*. A major nuclear or radiological incident has the potential to affect the raw materials and tools of industry. Accordingly, it will be necessary to monitor the industrial sector including materials, equipment, and finished products to restore normality, sustain the viability of the economy, and support critical infrastructure. Following the recent Fukushima Dai-ichi NPP incident, it was discovered that contamination had entered a source of concrete from the Fukushima region and was incorporated into new housing construction. Other examples of inadvertent contamination have been identified in metal products coming from unmonitored foundries and factories, and there have been recent reports of contamination in finished consumer products. Structural damage from the precipitating nuclear or radiological incident can create avenues for contamination to enter the manufacturing process. Such vulnerability is a concern across all industries, especially food processors and healthcare product manufacturers, where contamination could be introduced into the matrix of the product through raw materials and water. This possibility illustrates the need to develop methods and sampling plans to assess not only surface but also volumetric contamination.

6.5.2.4 *Critical Infrastructure and Property.* Critical infrastructure and personal property affected by a major nuclear or radiological incident will need to be restored in an optimized fashion to aid in the recovery of the affected communities and ensure the health and safety of workers and members of the public. Long-term monitoring will be needed to support cleanup efforts and monitor the movement of radionuclides through the environment. Samples should be taken in multiple matrices such as air, water, soil, sludge, and construction materials. Ambient exposure rate measurements will be needed to assess the potential for external doses and guide decisions on usage rates and stay times within critical infrastructures and personal property. Recent guidance from DHS outlines a methodology for assessing critical infrastructure and developing reference levels for monitoring and release of property (DHS, 2008a). Once the cleanup phase is complete and the infrastructure restored, late-phase monitoring will continue to confirm that activity concentrations have been reduced or stabilized and that any residual hot spots have been identified and remediated.

6.5.3 *Release of Other Properties*

Much of the cleanup effort discussed in the previous sections focused on the remediation of contaminated land. However, the concern over radionuclide contamination goes beyond the land, and extends to items ranging from commodities to drinking water. There are other properties, such as public buildings, structures, private residences, and personal belongings that will likewise need to be addressed during the recovery process. In general, releasing the properties for reuse or recycle will be desirable from an economic point of view as well as the timeliness of the recovery.

Release of nonreal properties (*i.e.*, properties other than land and structures) lacks a consistent, systematic policy, and has been conducted on an *ad hoc* basis in the past. Although specific exemption levels exist in current regulations, releases of properties or materials often encounter obstacles due to lack of clarity in the applicable regulatory provisions concerning release and/or disposition (NA/NRC, 2002; NCRP, 2002b), especially in the recovery situation after a major nuclear or radiological incident.

In recent years, there has been a concerted effort to bring about uniform standards for the release of properties other than land and structures. Among the options is the release under unrestricted conditions (under the concept of *clearance*), for which IAEA (2004a; 2005a; 2005b), and lately the American National Standards Institute (ANSI, 1999; ANSI/HPS, 2013) have developed consistent standards. Such standards have not yet been factored into the U.S. regulatory system, thus the status of these release provisions are yet to be determined. Furthermore, the applicability of these standards to the release of materials following the occurrence of a major nuclear or radiological incident has not been fully evaluated because the guidance pertains to releases from controlled facilities. The current release standards for properties or materials with surface and volume contamination are discussed below.

6.5.3.1 *Surface Contamination*. For the past four decades, the United States surface activity guidelines for clearing personal property, material and equipment have been derived from the NRC Regulatory Guide 1.86, *Termination of Operating Licenses for Nuclear Reactors* (AEC, 1974). These criteria have been applied broadly by NRC and their Agreement States to nonreactor activities as well as by DOE for research, development and production activities. The guidelines are consensus- and measurement-based. In general, the cri- teria are divided into those for alpha-particle and beta-particle/gamma-ray emitters and include criteria for removable and total contamination on the property being cleared. The criteria are also applied to structures as well as material and equipment. Over the years, AEC (1974) activity guidelines have been supplemented by DOE and NRC (AEC, 1974; DOE, 1990; Gilbert *et al*., 1989; NRC, 1982). Table 6.1 illustrates the criteria including the changes that were made in subsequent guidance that includes the addition of a requirement that the corresponding average and maximum absorbed dose rates for beta-particle/gamma-ray emitters not exceed 0.001 and 0.01 mGy h^{-1} (DOE, 1990; NRC, 1982) and separate guidelines for tritium (DOE, 2008). These guidelines have also been used to control or clear buildings and structures.

The impact of widespread radioactive contamination on consumer commodities is informed by recent accidental melts of radioactive sources contaminating commercial products. For example, in 2012 there were two widely publicized incidents where hundreds of ^{60}Co-contaminated stainless steel pet bowls and tissue boxes were found in commerce in the United States (NRC, 2011). In both cases, the pet bowls and tissue boxes were imported from India. Contact radiation levels on the pet bowls were on the order of 0.25 μSv h^{-1} dose equivalent, but in the case of the tissue boxes, dose equivalent rates were typically ~0.07 mSv h^{-1} with some as high as 0.2 mSv h^{-1}. A similar situation several years ago involved a hospital that discovered a stainless steel pulley on a magnetic resonance imaging table contaminated with ^{60}Co and read ~0.08 mSv h^{-1} on contact.

This magnetic resonance imaging table had been in use for 3 y. All of these incidents were a result of inadequate control of radioactive sources that led to the sources being accidentally melted with other waste metals and inadvertently reprocessed into consumer products. If there were significant radiological surface contamination or activation products from a nuclear or radiological incident then such commodity contamination could become widespread. Further, damage to infrastructure may allow contaminated air and water to enter the manufacturing chain, additionally leading to the potential contamination of a variety of products. In the

TABLE 6.1—*Surface activity guidelines (AEC, 1974).*

Radionuclides[b]	Allowable Total Residual Surface Activity (Bq m^{-2})[a]		
	Average[c,d]	Maximum[e,f]	Removable[g]
Group 1 Transuranics, ^{125}I, ^{129}I, ^{227}Ac, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{231}Pa	167 (100 dpm/100 cm^2)	500 (300 dpm/100 cm^2)	33 (20 dpm/100 cm^2)
Group 2 Th-natural, ^{90}Sr, ^{126}I, ^{131}I, ^{133}I, ^{223}Ra, ^{224}Ra, ^{232}U, ^{232}Th	1,670 (1,000 dpm/100 cm^2)	5,000 (3,000 dpm/100 cm^2)	333 (200 dpm/100 cm^2)
Group 3 U-natural, ^{235}U, ^{238}U, and associated decay products, alpha-particle emitters	8,330 (5,000 dpm/100 cm^2)	25,000 (15,000 dpm/100 cm^2)	1,670 (1,000 dpm/100 cm^2)
Group 4 Beta-particle/gamma-ray emitters (radionuclides with decay modes other than alpha-particle emission or spontaneous fission) except ^{90}Sr and others noted above	8,330 (5,000 dpm/100 cm^2)	25,000 (15,000 dpm/100 cm^2)	1,670 (1,000 dpm/100 cm^2)
Tritium (applicable to surface and subsurface)[h]	N/A	N/A	16,700 (10,000 dpm/100 cm^2)

TABLE 6.1—(*continued*)

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[a] The International System of Units (SI) include three significant digits only for computational accuracy. And, as also used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by counts per minute measured by an appropriate detector corrected for background, efficiency and geometric factors associated with the instrumentation.

[b] Where surface contamination by both alpha-particle- and beta-particle/gamma-ray-emitting radionuclides exists, the limits established for alpha-particle- and beta-particle/gamma-ray-emitting radionuclides should apply independently.

[c] Measurements of average contamination should not be averaged over an area of >1 m^2. For objects of smaller surface area, the average should be derived for each such object.

[d] The maximum and average dose rates associated with surface contamination resulting from beta-particle/gamma-ray emitters should not exceed 2 mGy h^{-1} and 10 μGy h^{-1} absorbed dose, respectively, at 1 cm.

[e] The amount of removable material per 100 cm^2 of surface area should be determined by wiping an area of that size with dry filter or soft absorbent paper ("wipe"), applying moderate pressure, and measuring the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of surface area <100 cm^2 is determined, the activity per unit area should be based on the actual area and the entire surface should be wiped. It is not necessary to use wiping techniques to measure removable contamination levels if direct scan surveys indicate that the total residual surface contamination levels are within the limits for removable contamination.

[f] The maximum contamination level applies to an area of not >100 cm^2.

[g] This category of radionuclides includes mixed fission products, including the ^{90}Sr which is present in them. It does not apply to ^{90}Sr which has been separated from the other fission products or mixtures where the ^{90}Sr has been enriched.

[h] Property recently exposed or decontaminated should have measurements (wipes) at regular time intervals to ensure that there is not a buildup of contamination over time. Because tritium typically penetrates material it contacts, the surface guidelines in Group 4 are not applicable to tritium. DOE has reviewed the analysis conducted by the DOE Tritium Surface Contamination Limits Committee (Johnson *et al.*, 1991), and has assessed potential doses associated with the release of property containing residual tritium. DOE recommends the use of the stated guideline as an interim value for removable tritium. Measurements demonstrating compliance of the removable fraction of tritium on surfaces with this guideline are acceptable to ensure that nonremovable fractions and residual tritium in mass will not cause exposures that exceed DOE dose limits and constraints.

example cases discussed above, the media coverage of a contaminated product raised the public concern, and most were recovered for proper disposal. Without proper controls of radiological waste in an incident recovery or restoration phase, the potential for the creation of contaminated consumer products could result in secondary public health issues and adverse economic impacts.

In 1999, ANSI issued, *Surface and Volume Radioactivity Standards for Clearance* (ANSI, 1999; ANSI/HPS, 2013). The consensus standard attempted to apply a more dose-based approach to the criteria provided. The authors indicated that the screening criteria in ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) provided a reasonable expectation that doses to members of the public from use of cleared materials and equipment would be <10 μSv y^{-1} TEDE. However, the scope or applicability of the standard was limited to materials and equipment; structures and lands were excluded. Unlike AEC-based criteria (AEC, 1974), which have been approved for use at NRC- and DOE-regulated facilities, the ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) values must be approved on a case-by-case basis. The values are arranged in four groups where the average allowable residual activity levels range from 0.1 to 100 Bq cm^{-2} or 0.1 to 100 Bq g^{-1} with averaging areas/volumes not exceeding 1 m^2 for area or 1 m^3 for volume. Although the ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) screening table does not contain a limit for maximum or removable activity, the standard indicates that no single measurement may exceed the table values by a factor of 10. It gives no separate values for removable contamination and only states that they may be used when appropriate. Table 6.2 compares the respective screening levels for a number of radionuclides likely to be associated with RDD and IND terrorist acts.

ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) standard screening levels were selected to provide a reasonable expectation that doses to members of the public exposed to the cleared material or equipment are likely to be <0.01 mSv y^{-1} effective dose, which is the dose defined as "negligible individual dose" in NCRP Report No. 116 (NCRP, 1993)[6] and elaborated in NCRP Report No. 141 (NCRP, 2002b). However, doses can vary depending on the distribution of the residual activity, the actual use of the property, verification survey techniques, and other factors. In most cases, potential doses from materials and equipment at the average allowable residual activity levels listed in ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) will be well below the negligible dose, especially given the conservative

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[6] Note that the negligible individual dose in NCRP Report No. 116 is an annual effective dose per source or practice.

TABLE 6.2—*Comparison of surface activity guidelines for structures.*[a,b]

Radionuclide	RESRAD-BUILD Dose-Base Concentration Guidelines in Bq m^{-2}				ANSI/HPS Standard (Bq m^{-2})	NRC Screening Guidelines[c] (Bq m^{-2})
	Residential Use at		Commercial Use at			
	1 mSv y^{-1}	0.04 mSv y^{-1}	1 mSv y^{-1}	0.04 mSv y^{-1}		
^{241}Am	1.3×10^4	5.2×10^2	3.0×10^4	1.2×10^3	1×10^3	4.44×10^1
^{252}Cf	1.7×10^4	6.7×10^2	9.2×10^4	3.7×10^3	1×10^4	1.44×10^2
^{244}Cm	2.3×10^4	9.3×10^2	5.4×10^4	2.2×10^3	1×10^4	8.14×10^1
^{60}Co	2.9×10^4	1.2×10^3	8.2×10^4	3.3×10^3	1×10^3	1.18×10^4
^{137}Cs	1.2×10^5	4.8×10^3	3.52×10^5	1.41×10^4	1×10^3	4.81×10^4
^{192}Ir	1.0×10^5	4.1×10^3	3.0×10^5	1.2×10^4	1×10^4	1.22×10^5
^{210}Po	3.1×10^5	1.3×10^4	7.4×10^5	3.0×10^4	1×10^3	4.07×10^3
^{238}Pu	1.2×10^4	4.4×10^2	2.7×10^4	1.1×10^3	1×10^3	5.18×10^1
^{239}Pu	1.0×10^4	4.1×10^2	2.4×10^4	9.5×10^2	1×10^3	4.81×10^1
^{226}Ra	2.5×10^4	1.0×10^3	6.6×10^4	2.6×10^3	1×10^3	1.8×10^3
^{90}Sr	8.1×10^5	3.3×10^4	1.8×10^6	7.4×10^4	1×10^4	1.44×10^4

[a] RESRAD-BUILD dose-base concentrations are presented for two dose criteria from the DOE operational guidelines manual (Yu *et al.*, 2009). The guidelines are proportional to dose.

[b] ANSI/HPS (2013) does not apply to structures, however it is presented for illustrative purposes only. The screening criteria in ANSI/HPS N13.12 provided a reasonable expectation that doses to members of the public from use of cleared materials and equipment would be <10 μSv y^{-1} TEDE.

[c] NRC screening guidelines were developed to satisfy 0.25 mSv y^{-1} TEDE plus adhere to the ALARA principle. They were obtained from NUREG-1757, Volume 2, Table H.1 (Schmidt *et al.*, 2006), or were calculated by using decontamination and decommissioning (NRC, 2001) by following the NRC guidance.

approaches used in clearing property. However, there are circumstances where doses could be an order of magnitude higher than the negligible dose but still below the annual 1 mSv TEDE NRC (2014a) limit to members of the public imposed on holders of NRC material licenses. Quantitative assessments of the AEC (1974) levels indicate similar expectations (Chen, 1993). In any case, ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) and AEC (1974) criteria may not be specifically applicable to emergency response actions associated with a nuclear or radiological incident. They are developed for routine controlled situations given considerations in applying the ALARA principle that would be different in the case of an incident situation. DHS PAGs and associated operational guidelines (Yu *et al.*, 2009) provide additional information on factors that could be considered in applying the ALARA principle following such an incident.

As noted above, AEC (1974) screening values have been and are applied to structures. More recently, however, dose-based approaches have been recommended by NRC and DOE for clearing of structures from licensed or authorized use. Both DOE and NRC recommend the use of RESRAD-BUILD (Yu *et al.*, 2003) to compute doses from potential uses of structures and select remedies in applying the ALARA principle below the 0.25 mSv y^{-1} TEDE constraint for clearance of real property. DOE permits the use of the surface guidelines shown in Table 6.2 but recommends the dose-based approach to applying the ALARA principle where the surface guidelines are not appropriate. NRC has issued screening criteria that may be applied in lieu of a dose-based analysis. The DOE Operational Guidelines manual (Yu *et al.*, 2009) also includes derived screening values that are dose-based and are compared to NRC screening values in Table 6.2.

IAEA Safety Guide No. RS-G-17, *Application of Concepts of Exclusion*, *Exemption and Clearance* (IAEA, 2004a), also provides screening values for clearance of material and equipment from normal operations, however they only provide the information in terms of volumetric (Bq g^{-1}) activity levels.

6.5.3.2 *Volume Contamination*. Most of the volumetric contamination from a major nuclear or radiological incident is associated with soils in the affected lands. In general, the volumetric residual concentrations in soils have been derived from the cleanup guideline during the remediation process. In the conventional cleanup under the statutory regulatory provisions, the soil criteria for land (real property) have been based on dose or risk (Section 4.3.4.5).

As such, the derived soil concentrations may vary depending on the following assumptions: cleanup criteria based on dose or risk, future land uses, analytical approach and parameters used, and regulatory applications. Such variations are illustrated in Table 6.3, where soil concentrations have been derived from the following examples:

- site-specific derivation by the RESRAD code (Yu *et al*., 2001) assuming a resident farmer land-use scenario based on a realistic analysis (*i.e.*, probabilistic estimated at 50th percentile);
- generic screening levels based on an effective dose criterion of 0.25 mSv y^{-1} for unrestrictive release of a licensed facility (NCRP, 1999; Schmidt *et al*., 2006); and
- EPA generic soil screening guideline based on a lifetime cancer risk of 10^{-6} (EPA, 2000).

Also shown in Table 6.3 are the clearance standards published by ANSI/N13 standards (ANSI/HPS, 2013), which is based on consideration of a spectrum of release scenarios (*i.e.*, material reuse, recycle or disposal) for a dose criterion of 0.01 mSv y^{-1} TEDE. It is to be noted that none of these concentration levels are specifically tailored to a nuclear or radiological accident or to a terrorist incident but may be useful as benchmarks.

6.6 Economic Monitoring

It will be important to monitor economic and socio-demographic indicators, both to measure whether progress is being made and to determine when goals have been reached. Prior to any nuclear or radiological incident, it will be prudent to begin the process of collecting and organizing economic and socio-demographic data at the local level. Having access to information about all aspects of the area will be helpful to develop resiliency. During the recovery the data should continue to be collected, as it will be helpful in deciding what goals should be set, the methods by which these goals will be achieved, and any needed changes in goals or methods over time.

The specific economic and demographic variables to measure will depend on the goals, but will likely include employment by sector, output by sector, and gross domestic (or state/local) product. Sectors will include industry, agriculture, services, government and tourism. The flow of resources into and out of the area will need to be evaluated. It will also be essential to monitor vacancy rates of both commercial buildings and residential housing markets in conjunction with prices and rents over time. Population numbers by age and gender will need to be collected and updated, as will school attendance rates. Depending on the area, tourism data may be relevant as well.

TABLE 6.3—*Comparison of dose-based RESRAD derived cleanup guidelines with published dose- and risk-based screening guidelines (or limits) in Bq g^{-1}.*

Radionuclide	RESRAD[a] Computed Concentration Based on		NRC	EPA	NCRP Report No. 129 (NCRP, 1999)	ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) Standard
	1 mSv y^{-1}	0.04 mSv y^{-1}	Screening Guideline[b]	Soil Limit[c,d]	Screening Limit Soil[e]	Clearance Limits[f]
^{241}Am	9.2×10^{1}	3.7×10^{0}	7.8×10^{-2}	9.6×10^{-2}	3.3×10^{-1}	1.0×10^{-1}
^{252}Cf	3.2×10^{0}	1.3×10^{-1}	8.9×10^{-2}	—[g]	3.4×10^{-1}	1.0×10^{0}
^{244}Cm	3.0×10^{2}	1.2×10^{1}	1.6×10^{-1}	2.7×10^{-1}	4.8×10^{-1}	1.0×10^{0}
^{60}Co	5.7×10^{-1}	2.3×10^{-2}	1.4×10^{-1}	1.3×10^{-3}	2.3×10^{-2}	1.0×10^{-1}
^{137}Cs	2.3×10^{0}	9.2×10^{-2}	4.1×10^{-1}	2.3×10^{-3}	1.1×10^{-1}	1.0×10^{-1}
^{192}Ir	6.3×10^{0}	2.5×10^{-1}	1.5×10^{0}	—[g]	4.4×10^{-1}	1.0×10^{0}
^{210}Po	2.0×10^{1}	8.1×10^{-1}	3.3×10^{-1}	—[g]	4.4×10^{-2}	1.0×10^{-1}
^{238}Pu	1.6×10^{2}	6.2×10^{0}	9.3×10^{-2}	6.7×10^{-2}	3.2×10^{-1}	1.0×10^{-1}
^{239}Pu	1.4×10^{2}	5.7×10^{0}	8.5×10^{-2}	5.9×10^{-2}	2.9×10^{-1}	1.0×10^{-1}

TABLE 6.3—(*continued*)

Radionuclide	RESRAD[a] Computed Concentration Based on		NRC	EPA	NCRP Report No. 129 (NCRP, 1999)	ANSI/HPS (ANSI, 1999; ANSI/HPS, 2013) Standard
	$1\ \mathrm{mSv\ y^{-1}}$	$0.04\ \mathrm{mSv\ y^{-1}}$	Screening Guideline[b]	Soil Limit[c,d]	Screening Limit Soil[e]	Clearance Limits[f]
^{226}Ra	9.9×10^{-2}	4.0×10^{-3}	2.6×10^{-2}	4.8×10^{-4}	3.7×10^{-3}	1.0×10^{-1}
^{90}Sr	9.3×10^{0}	3.7×10^{-1}	6.3×10^{-2}	2.6×10^{-3}	1.4×10^{-2}	1.0×10^{0}

[a] RESRAD probabilistic analysis concentrations are based on 50th percentile values from resident farmers.

[b] NRC screening guidelines were developed on the basis of 0.25 mSv $\mathrm{y^{-1}}$ TEDE. The values were obtained from NUREG-1757, Volume 2, Table H.2 (Schmidt *et al*., 2006), or were calculated by using decontamination and decommissioning (NRC, 2001) and following NRC guidance. It is noted that these values were developed using conservative assumptions and parameters.

[c] EPA soil screening limits were developed on the basis of a lifetime cancer risk of 1×10^{-6}. They were obtained from the EPA *Soil Screening Guidance for Radionuclides: Appendix A* (EPA, 2000).

[d] Screening limits were the smallest (most conservative) values among different exposure pathways, including ingestion of homegrown produce, direct ingestion of soil, inhalation of fugitive dusts, external radiation, and ingestion of groundwater (migration to groundwater). Radioactive decay was accounted for, and the dilution factor for the migration to groundwater was 20.

[e] NCRP (1999) soil screening limits were developed on the basis of 0.25 mSv $\mathrm{y^{-1}}$ effective dose and considered different land uses. The values listed are the most restrictive ones.

[f] ANSI/N13.12 standards (ANSI, 1999; ANSI/HPS, 2013) were developed for clearance of material containing radionuclides with a primary dose criterion of 0.01 mSv $\mathrm{y^{-1}}$ TEDE.

[g] The value is not available from the EPA document.

By examining these data, decisions can be made about the effectiveness of various programs and policies in achieving the stated goals. Changes in the programs can be considered and, if implemented, evaluated by continually assessing the data.

6.7 Environmental Monitoring and Cessation of Monitoring

> With stakeholders' participation and agreement, monitoring of radioactive material may eventually be terminated. This process will remain an integral component in optimized decision making.

In the immediate aftermath following a major release of radioactive materials from an accidental or malevolent act, there will be significant redistribution of contamination throughout the environment. However, due to weathering, physical decay, and the movement of surface deposition into the soil, radionuclides will become less bioavailable and the transfer into plants and animals will rapidly decrease (IAEA, 2006b). Further, as remediation efforts proceed, contamination will be removed and sequestered. Still, a significant level of monitoring may be needed for many years, particularly for long-lived radionuclides. Monitoring will be used to assess the progress of recovery efforts and the potential future risk of exposure to guide behaviors and establish a return to normalcy. Millions of samples may be collected over a period of years.

While certain subsections of the environment may continue to exhibit a redistribution of radioactive activity over time (*e.g.*, forests), the general trend will be toward the reduction and stabilization of contamination levels. Once stabilization has occurred, further removal will be governed by radioactive decay rates that may be dominated by one or a suite of long-lived radionuclides. Monitoring will be needed to confirm that only radioactive decay is influencing the removal of contaminants and the effects of weathering and resuspension have diminished. As of the IAEA (2006b) report there had been a noticeable decrease in the transfer of radionuclides to plants and animals in the earlier years, but in the period of 10 to 20 y following the Chernobyl nuclear reactor accident, there were no significant further reductions. The long-term effective half-life has been difficult to quantify precisely but the decay appears to be in the range of 3 to 7 % per year (IAEA, 2006b).

Monitoring may also include the potential radiological effects on the ecological system. The emerging issues of the effects on the environment have recently been recognized following the Chernobyl nuclear reactor accident (IAEA, 2006a) and also by ICRP in the revised system of protection (ICRP, 2009). Ongoing efforts are being devoted to growing concerns over the potential ecological impacts that may be caused by radioactive contamination (Copplestone *et al.*, 2001), and so monitoring of the ecological system is being recognized as an important component of environmental protection.

Once the remediation goals have been achieved and an apparent equilibrium has been established, the need for an intensive monitoring program will diminish. However, as long as any contamination persists in the environment, periodic surveys will be needed to confirm previous findings and to reassure members of the public, especially in the areas of food and agriculture. Food monitoring will need to continue as long as any products exceed intervention levels. Routine annual environmental monitoring may be adequate and, as the decay rate becomes dominated by very long-lived radionuclides, a 5 y survey frequency may prove sufficient. Eventually, some access control may be lifted due to the continued remediation effort, or other mitigation measures might be implemented, such as containing runoffs from a contaminated forest that previously had restricted access. With stakeholders' participation and agreement, monitoring can eventually be terminated. This process will remain an integral component in optimized decision making.

6.8 Long-Term Management

While remediation efforts may be successful at removing or sequestering most radioactive contamination, it may not be possible to reduce activity levels in the affected area to pre-incident levels. This may be due to technical or resource limitations or logistical issues such as the existence of complex topographies like those of forests and parks. To the extent that these residual levels pose an unacceptable level of risk, it will be necessary to control exposures by a variety of management methods. Authorities must also be aware of the potential for contamination to be transferred from one compartment to another resulting in unintended consequences. For instance, following the Chernobyl nuclear reactor accident, weathering and human activity reduced contamination in urban settings, but remediation procedures resulted in increased contamination in sewage treatment facilities and sludge storage areas (IAEA, 2006b).

6.8.1 *Food and Agriculture*

The control of exposures from the ingestion pathway will continue to rely on monitoring as a key tool. However, the intensity of monitoring should decrease with time as residual radionuclides become less bioavailable. Beyond the first cycle of harvest after a major release, the attention of officials should turn to making decisions about future use of agricultural lands for planting crops and grazing animals. Certain soil additives and fertilizers may be helpful in reducing the uptake of radionuclides into plants and grasses. Soil samples in conjunction with modeling will also assist in making the decision whether to plant or to find alternative uses for the land (Yu *et al*., 2009).

The experience following the Chernobyl nuclear reactor accident demonstrated that it was possible to salvage animals that had been contaminated by using a combination of methods. One of the most effective options was the use of clean feed prior to slaughter, which allowed for the clearance of activity from tissue. Prussian Blue was also used successfully, although finding a plentiful source at an affordable price could be a challenge especially for a large operation. Finally *in vivo* monitoring can be implemented to identify animals that are safe to market. The use of these methods can help avoid the consequences of carrying out a mass slaughter in the absence of other interventions (IAEA, 2006b).

A campaign to educate and inform consumers about the risks of radionuclides in food will play an important role in reassuring them and giving them the tools to manage their food supply without needing to abandon their normal diet. With the exception of a very large-scale incident that impacts a major part of the food supply, it should be possible to maintain the majority of the diet from normal sources or by importing certain foods from unaffected regions. In the long term, the biggest impacts would likely be felt by subpopulations who obtain a significant part of their diet from wild sources such as mushrooms, berries, and wild game. Information on alternative preparation methods can also help to ensure that most contamination is removed from the edible portion of the food product. Finally, if it is found necessary to condemn certain crops or food sources, consideration should be given to finding alternative uses that may continue to support the producer, and by extension, the community, both economically and socially.

6.8.2 *Water*

As discussed above, the aquatic pathway represents a relatively small fraction of the total exposure risk to humans due to dilution, sedimentation, and rapid clearance from the soft tissue of fish. However, in areas where it has been shown that there is the potential for redistribution of radionuclides from sediments, it may be necessary to control the use of water and the consumption of fish. In regions that rely on surface water for irrigation or other purposes, it may be necessary to institute additional flood controls;

however, as time passes the risk from these sources should significantly diminish.

6.8.3 *Forests and Recreation Areas*

Since decontamination will be extremely challenging and likely ineffective in a forest environment, radiation levels will probably remain elevated, subject only to weathering and physical decay. Radiation levels may also show seasonal variations. Therefore, it will be necessary to restrict access and place limitations on normal activities to reduce human exposure. Controls will be needed to limit both external exposures from time spent in the forest as well as internal exposures from inhalation of resuspended radionuclides and ingestion of game or other foods normally obtained in the forest. Decision makers and stakeholders should also consider restrictions on the use of contaminated timber for building and heating, as these activities can contribute to both external and internal exposures, with internal exposure being the larger contributor to population dose. In regard to the burning of wood and the increased inhalation hazard, fire control will be a key management tool in limiting doses.

In the fullest application of the optimization process, all actions taken to reduce exposures need to be considered in the context of the social and economic concerns of the affected areas, and the desire to return the whole community to a new normality. Stakeholder participation in the decision-making process is necessary to help manage expectations and increase the acceptance of deviations from pre-incident lifestyles and behaviors.

7. Summary of Recommendations

A resilient community is one that is able to return to near-normal conditions in an expedited manner after a catastrophic incident. Recognizing that the response for late-phase recovery after a nuclear or radiological terrorist attack or nuclear reactor accident is incident and site specific, this Report emphasizes general principles for circumstances that go well beyond those experienced in conventional cleanups. Important issues are identified and recommendations made to enhance and strengthen the approach to late-phase recovery and decision making, specifically when the incident results in widespread contamination with radioactive material.

Given the potential for wide-area contamination following a major nuclear or radiological incident, the traditional statutory approach to remediation and cleanup may not be applicable in either scope or approach. Optimization emerges as a balanced strategy to address the complex issues facing the long-term recovery process. The optimization approach embraces the need for stakeholder engagement in decision making, the integration of societal factors in radiation protection decisions, the importance of risk communication, and the commitment to long-term monitoring strategies. A sound recovery plan is one based on a well-developed optimization process and emphasizes the goal of community resilience. Community resilience should be integrated into all recovery plans to improve both the effectiveness and efficiency of recovery.

Lessons have been learned from previous incidents that involved substantial releases of radionuclides into the environment. The protection of people living in contaminated areas has attracted national and international attention, notably following the 1986 Chernobyl nuclear reactor and the 2011 Fukushima Dai-ichi NPP accidents.

ICRP issued guidance in Publication 103 (ICRP, 2007) to establish a framework for protecting people under various exposure situations (planned, emergency and existing) and Publication 111 (ICRP, 2009) specifically addressed the protection of people living in long-term contaminated areas.

New knowledge on late-phase recovery will be gained from the ongoing efforts associated with the Fukushima Dai-ichi NPP accident of 2011 (GOJ, 2011; 2012). However, the limited experience and knowledge to date in coping with late-phase issues, makes preparing for a major nuclear terrorist incident or reactor accident challenging. As more information becomes available, identification of recovery problems and their potential solutions will enable communities to modify and integrate late-phase actions into their overall preparedness efforts.

7.1 National Strategy Promoting Community Resilience

> A comprehensive national strategy should be developed that focuses on promoting community resilience as the most favorable preparedness approach for responding to and recovering from major nuclear or radiological incidents involving widespread contamination.

Establishing a resilient society prior to and after an incident is key to the recovery process. Toward this end, measures should be taken to address every facet of community life including housing, transportation, infrastructure, public health, economy, social services, and support. FEMA published NDRF (FEMA, 2011a) specifically to address recovery issues. This framework entails a flexible structure that enables disaster recovery managers to operate in a unified and collaborative manner. It also focuses on how best to restore, redevelop and revitalize the health, social, economic, natural and environmental fabric of the community, and build a more resilient society.

However, more guidance is needed on developing and incorporating explicit and effective measures that enhance community resilience, particularly when the recovery effort involves widespread radioactive contamination (Section 4). Effective measures should consider all the important components of the response and either qualitative or quantitative attributes that can gauge the robustness of the response. These attributes include resource vigor (which can be evaluated by performance, diversity and redundancy), adaptive capability, institutional memory, innovative learning, and connectedness (Longstaff *et al.*, 2010). Further, the effort to strengthen community resilience will need to include the development of a hierarchical structure with criteria for setting priorities for a timely response, incorporating important political, economic and cultural forces (Section 5).

Because the recovery effort is community-based, care should be taken to ensure that relevant options and decisions are commensurate with the needs of the community. Available resources should be tailored to address the specific required actions and surge resources should be identified.

The effort to strengthen resilience involves two important strategies. The first strategy is planning to inform and prepare communities for major nuclear reactor accidents or terrorist attacks with RDDs or INDs and subsequent widespread contamination. Although pre-incident planning typically addresses the support and logistic issues, the effort may also include strengthening building structures against damage from explosions or shock waves, providing shelter for the affected populations, making population warning systems available, and developing methods that can be readily deployed for decontaminating building surfaces.

The second strategy is to facilitate an orderly and speedy recovery effort. This issue is particularly important when extensive contamination is involved. The possibilities may include:

- development or adaptation of sufficiently flexible policies to accommodate the remediation effort;
- establishment of funding structures for extensive cleanup efforts;
- identification of appropriate radioactive waste storage and disposal areas;
- identification and development of appropriate decontamination techniques for effective and efficient cleanup efforts;
- development of a well-coordinated personnel response structure; and
- other socio-economic infrastructures to help facilitate late-phase recovery actions.

Some of these issues are further elaborated in Sections 7.2 through 7.8.

7.2 Late-Phase Response Integration into Emergency Planning

> Late-phase response following a major nuclear or radiological incident involving widespread contamination should be integrated into national, state and local government emergency response planning and regularly included in response exercises.

The preparedness effort should be integrated into the overall response plan to a major nuclear or radiological incident to ensure a robust defense. Although the potential consequences from an incident may be highly uncertain, general considerations for proper preparedness should be included in any major emergency planning activity. The most difficult task following an incident may be the eventual recovery of society's most affected areas. The very challenging task of long-term site remediation and restoration will inevitably require considerable resources and efforts.

Late-phase actions in response to a radiological terrorist attack or major reactor accident will require addressing a multifaceted disaster that touches every aspect of society. Recognizing that the complexity of a cleanup is highly dependent on site-specific factors, several issues are particularly critical to the decision-making process (Section 5) and include how to:

- characterize the governing cleanup principles;
- incorporate incident-specific conditions and other relevant parameters in the remediation strategy;
- identify, develop, analyze and prioritize options; and
- reach consensus among stakeholders and decision makers.

To facilitate decision making, numerous diverse issues will be identified and then evaluated; these issues include public policy, science and technology, socio-economic considerations, public relations, and communication. Some of these broad issues have surfaced in recent exercises to cope with radiological terrorism (DHS, 2007a; EPA, 2010), and have been specifically considered in recent nuclear or radiological incidents (IAEA, 1988; 2006b). These issues require considerable study and deliberation, and therefore warrant incorporation into preparedness planning. Specific issues include:

- evaluation of potential land-use options in a major incident involving widespread contamination with radioactive material, including public and private properties, and commercial and residential uses;
- identification of potential locations for waste storage (temporary or long term), transportation of waste, and disposal of radioactive waste or wastewater generated by decontamination activities;
- compilation of available and feasible decontamination technologies for remediation of properties and wide-area applications;
- identification and assurance of funding resources and alternate economic plans;
- development of possible adaptive mechanisms (such as self-help programs) and resources for the education and training of members of the public; and
- establishment of a long-term monitoring program for public health, the environment, and commodities.

The information developed will enhance the protection of society by alleviating the initial impact from incidents and become an important component of the overall defense strategy in building a resilient community.

Although late-phase recovery efforts are not considered emergency actions, they nonetheless are an integral component of the overall response to a major nuclear reactor accident or radiological terrorist attack. Any actions taken during the early or intermediate phase (such as removing radioactive debris to facilitate emergency access) will influence the response during the late phase. Due to the complexity of late-phase issues, it is advantageous to start planning for long-term recovery at the earliest time after the incident has occurred. Such a strategy will ensure an improved and more balanced overall response and minimize potential discontinuities in planning. This approach is best accomplished by aligning the key components of the NDRF (FEMA, 2011a) with those of the NRF (DHS, 2008b). These documents are described in detail in Appendix G.

7.3 Site-Specific Optimization

Site-specific optimization for managing widespread contamination from radioactive material should be fully embraced to maximize community benefit.

Optimization is one of the three principles of radiation protection and should guide the selection of remediation actions for late-phase recovery. Optimization is generally recognized to have the same meaning as the ALARA principle (NCRP, 1993). ICRP Publication 103 (ICRP, 2007) states:

> "The principle of optimisation is defined by the Commission as the source related process to keep the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual doses as low as reasonably achievable, taking economic and societal factors into account."

The optimization approach is discussed further in ICRP Publication 111 (ICRP, 2009), which characterizes the late-phase exposure as an "existing exposure" situation for which a target reference level is designated. Application of the ALARA principle should always be emphasized in any deliberate effort to reduce radiation exposures below reference levels as much as possible taking cost and societal issues into account. Along with the optimization approach, ICRP also emphasizes the need to engage stakeholders in the decision-making process, recognizing that the process should maintain flexibility.

For protection of populations living in contaminated areas in the aftermath of a major radiological accident or terrorist act, the guidance follows the existing exposure situation as laid out by ICRP Publication 111 (ICRP, 2009). However, incidents of such nature have been rare and relatively little knowledge or experience has been accumulated on the state of the community and the general environment that would be faced in late-phase recovery. In addition, the relevant issues are likely to be incident and community specific, thus adding to the complexity of formulating a systematic approach to long-term remediation. Much of the relevant information can only be inferred from lessons learned from the few disastrous nuclear reactor accidents or radiological incidents that have resulted in widespread contamination. This reality exists despite the fact that remediation of radioactive contamination has been extensively undertaken in the past several decades, and well-established cleanup approaches with advanced technologies have been developed and deployed.

Application of conventional methods to remediate the widespread contamination created by a major nuclear reactor accident or terrorist act may be inadequate or otherwise difficult to deploy in a timely manner and so new conceptual approaches will be needed. Some of the potential differences are discussed here.

1. Past nuclear reactor accidents such as those that have occurred at Chernobyl and Fukushima have caused unprecedented environmental and economic consequences, and resulted in large contaminated areas on the order of hundreds of thousands of square kilometers and a high level of complexity (GOJ, 2011; 2012; IAEA, 2006a; IAEA/NEFW, 2011). An RDD or IND incident could likewise result in large areas of contamination, potentially reaching hundreds of city blocks (DHS, 2008a; FAS, 2002). Addressing this kind of widespread contamination requires a different knowledge base and set of experiences that cannot be directly translated from the conventional (*i.e.*, regulatory driven) cleanup experiences. The remediation activities in these incidents are likely to have additional constraints in terms of resources, time and technology.
2. While the long-term health risk has been a primary consideration in the current statutory cleanup requirements (NCRP, 2004), the optimization process for late-phase

remediation issues will entail far broader considerations for the disrupted communities. The response toward recovery will likely involve a spectrum of societal issues in addition to considering the potential health risks from the radioactive contamination. An incident-disrupted community will need support toward recovery in areas that include housing, infrastructure, business (economic revitalization), behavioral health (emotional or psychological), public health and care, as well as mitigation activities (FEMA, 2011a). Toward this end, the responsible authorities and the communities will have to work together to decide on the best path forward while exercising great latitude and flexibility to consider the many important issues competing for priority. To accomplish this, the optimization process necessarily becomes the favored approach to decision making, balancing the many important and competing factors to meet the community's needs. Consequently, the pre-established statutory cleanup criteria, which are largely based on long-term health-risk considerations and focused on specific contamination conditions, may serve as a reference for optimization consideration, but the extreme circumstances of some scenarios may warrant alternative criteria (Section 7.6).

3. The remediation strategy requires consideration of multiple land-use scenarios in decision making. The potential wide-area contamination will result in exposure to individuals from multiple sources from various land uses. Thus, the protection strategy can no longer focus on remediation of just one limited area of the contaminated land as in the conventional approach, but it should instead weigh the overall remediation decisions over numerous, possible land-use options distributed over a large contaminated area. The dose reduction strategy should not rely on simply protecting the "maximally-exposed individual," but instead on managing the overall dose over time to the affected populations with clearly established priorities. Such a strategy may include access control to highly contaminated lands and modifying individual behaviors (*i.e.*, altering exposure pathways), in conjunction with performing the necessary cleanup effort, while taking into account radioactive decay and weathering effects in the process. The priority for cleanup should be developed as part of the management strategy through the optimization process. The management priority is to continue to reduce doses below reference levels as recommended by ICRP (2009) with an appropriate

stakeholder-involved policy formulated to address specific remediation issues (Section 7.3, Item 4).

4. Long-term monitoring and management is a key element of the optimization process. The process includes long-term management of any residual activity from radionuclides that continue to exist in the environment and the resulting radiation exposure. Monitoring might include health conditions among the exposed populations; environmental contamination (such as reconcentration of activity or recontamination due to weathering effects or human activities); and residual contamination in foodstuffs, infrastructures, properties, drinking water, and commodities. Data should also be collected that include economic metrics to monitor the financial sustainability of the region and economic welfare of the families therein. Throughout the monitoring process, proper communications should be maintained with stakeholders until a consensus decision can be reached to discontinue the monitoring activities (taking into account radioactive decay and other factors such as weathering). Consequently, it is important to formulate a cleanup policy with long-term monitoring and management in mind (Section 7.6, Item 4).
5. Remediation decisions should consider both individual dose and collective dose. Although the objective of the optimization process is to effectively manage the reduction in doses for individuals occupying a contaminated area through the ALARA principle, an explicit demonstration of the effectiveness of such actions, such as through the representative individuals concept (ICRP, 2006), will be difficult. Unlike the conventional approach based on certain postulated land-use scenarios to derive cleanup criteria, a major nuclear accident or radiological terrorist act could result in multiple land-use scenarios with different contamination levels throughout the contaminated zone of interest. The situation is further complicated when the background radiation levels are increased several fold by the presence of multiple radiation sources. Due to the probabilistic nature of the potential exposure scenarios to which an individual may be subjected, it is difficult to ascertain individual doses for radiation protection management purposes other than by direct monitoring of the individuals in the affected populations for an extended period of time. Thus, it is important that collective doses of the affected populations also be assessed to aid the dose

management approach in the optimization process. It may be more feasible and desirable to assess collective doses for population subgroups (such as children in school yards or people traveling on main traffic highways). The approach to reducing doses to affected populations can thus be made more effective by prioritizing cleanup activities in areas of recognized significance. As such, collective dose assessment (in addition to individual dose assessment) should be included in the repertoire of methods for managing long-term contamination issues. In doing so, care should be exercised that "conservatism" (*i.e.*, the tendency to exaggerate or intentionally overestimate the dose for the purpose of protection) should not become a substitute for "uncertainty," because dose assessment results are intended to serve for evaluating and comparing cleanup options rather than for protection purposes. Thus, deliberate use of conservatism (or lack of realism) in dose assessment would misrepresent the results and thereby could potentially and inappropriately skew the decision making.

7.4 Stakeholder Engagement and Empowerment

Stakeholder engagement and empowerment underpins the optimization process and should be an integral part of late-phase response and recovery actions, and, accordingly, in consensus building during the decision-making process.

The optimization process is designed to address the broad and complex issues involving remediation of a widely contaminated area, with its primary objective to achieve a timely restoration and recovery of the affected communities from a highly perturbed state.

Toward this end, key elements of the associated decision-making process include identifying and mitigating potential health risks, restoring key infrastructures, addressing public financial burdens, and resuming normal commercial activities, as well as balancing the roles and interests of affected stakeholders. However, society as a whole has little experience with such processes (Eraker, 2004; Yassif, 2003). While existing cleanup guidance may serve as a convenient benchmark within its targeted scope, as discussed earlier, the much more complex societal issues will require an optimization process to guide the selection of the most appropriate remediation decisions. A decision on any remediation approach should be weighed against the potentially large costs and other socio-political factors to be borne by society. Thus, achieving "optimization" requires a transparent approach backed by a sound rationale that satisfactorily balances health and environmental risk goals with the many other priority considerations. The development and implementation of such an optimization process will require extensive involvement and input from various stakeholders during key decision-making steps, a process advocated by the Presidential Commission on Risk Assessment and Risk Management (Omenn *et al.*, 1997a; 1997b).

The collective cleanup experiences gained from the existing statutory cleanup activities are valuable input to the overall optimization effort. For example, in managing the long-term objective of remediation, a decision hierarchy may be established as part of the strategy that sets the priority and scope of the effort. In this process, various stakeholder groups should be involved and coordinated for collective decision making. A rigorous cleanup of a particular land area may favor the dose reduction to certain population subgroups of higher priority (such as children in school yards), but it could also delay the similar remediation actions at other locations (such as forests and other remote and thinly populated areas). Further, the remediation actions will likely generate large amounts of radioactive waste that require temporary storage or disposal arrangements adjacent to the contaminated sites that may be occupied by different sectors of the population. Decision making in such circumstances will be complex, often involving intertwined and conflicting issues among stakeholders, and will require an extraordinary approach and effort to reach consensus.

For stakeholder engagement involving radiation protection issues, HPS (2010), IRPA (2009), NA/NRC (2006; 2009), NCRP (2004), and Omenn *et al.* (1997a; 1997b) have published useful guiding principles (Section 4.4.4.1). These guiding principles provide field-tested and sound counsel to radiation protection professionals to engage successfully with stakeholders in decision-making processes that result in mutually agreeable and sustainable decisions.

In recent years, there has been a growing concern about civil preparedness to cope with major disruptions caused by natural disasters or terrorist acts. Recognizing government limitations and its effectiveness in responding to such major incidents, FEMA developed the "whole-community" approach for preparedness and response (FEMA, 2011b):

> "However, today's changing reality is affecting all levels of government in their efforts to improve our Nation's resilience while grappling with the limitations of their capabilities. In

> large-scale disasters or catastrophes, government resources and capabilities can be overwhelmed."

The whole-community approach advocates further engagement with stakeholders in the overall response effort. To this end FEMA seeks to initiate a national dialogue aimed at determining the best means by which residents, emergency managers, practitioners, organizational and community leaders, and government officials can collectively understand and assess the needs of the respective communities. The whole-community approach follows three principles: understand the basic needs of the whole community, engage and empower all parts of the community, and strengthen what works well in those communities on a daily basis. It is also supported by the following community strategic themes:

- understand community complexity;
- recognize community capabilities and needs;
- foster relationships with community leaders;
- build and maintain partnerships;
- empower local action; and
- leverage and strengthen social infrastructure, networks and assets.

Additionally, the whole-community approach further integrates the element of empowerment with stakeholder engagement for preparedness and response to disasters. This concept applies throughout all phases of an incident, and will be particularly important to the late-phase recovery effort since there are considerable complex and diverse issues to be addressed through the optimization process. Advancing these concepts also requires related actions by the government and responsible authorities to develop and implement appropriate policies to facilitate engaging and empowering stakeholders. For example, the creation and support of a citizen's self-help program both engages and empowers the stakeholders, as elaborated in the recommendations in Sections 7.5 through 7.8.

7.5 Communication Plan

A communication plan should be developed as an integral component of the preparedness strategy to ensure that messages are accurate, complete, understandable, and widely distributed.

Effective communication is necessary to incorporate, engage, encourage and empower stakeholders in all aspects of late-phase recovery. Any incident that causes widespread radioactive contamination will be of concern to the population living in the affected and surrounding areas. This concern is magnified when the potential consequences include significant human health worries, environment threats, and adverse economic impacts. Regardless of the origin of the incident, the affected communities will share a clear objective: the expeditious recovery from the disruption of society. Lessons learned from major disasters have identified effective communication as one of the most important areas needed for future improvement in responding to an incident (Section 7.8).

Effective communication is challenging in all phases of any emergency. The effort is further complicated by incidents involving the release of hazardous agents, particularly radioactive materials. As discussed earlier, the objective of the late-phase effort is to complete the recovery plan in the most expedient manner in order for the communities to rebound from their losses and to sustain the physical, social and economic well-being of affected populations. To achieve these objectives, it is essential that an appropriate communication plan be developed at every level of government and the private sector, including federal, state, tribal and local governments, together with nongovernment organizations including volunteer organizations, religious organizations, and other community or advocacy groups.

The importance of the communication function has been recognized by its designation in NRF (DHS, 2008b) as Emergency Support Function (ESF) #2 (Communications Annex) to support the response to non-wartime emergencies. ESF #2 is led by the National Communication System of DHS, whose function is to supplement the provisions under the National Telecommunications Support Plan. ESF #2 offers a nationwide mechanism for communication during an emergency.

Organizing the relevant sectors and stakeholders in coordinating the late-phase recovery effort requires effective communication approaches and practices (Section 7.4). For responses to major radiological or nuclear incidents, the communication effort should be oriented toward implementing the whole-community approach (FEMA, 2011b), as discussed in the recommendation of Section 7.4, to integrate all sectors of stakeholders into response planning and implementation.

In the late-phase optimization process, comprehensive communication plans also should be developed and integrated into all major recovery decision-making activities. A detailed communication strategy should identify specific target audiences and processes that will ensure timely, credible and clear messaging. The plan should allow for transparency in delivery as well as the effective use of various delivery channels and media (including social media). Feedback loops should be available so that two-way communication is facilitated throughout the decision-making process (Section 5.5.2).

7.6 Adaptive and Responsive Cleanup Strategies

> Adaptive and responsive cleanup strategies should be developed that facilitate the optimization process.

Although the scope and responsibilities of the national response to all hazard incidents are well structured and prescribed under the NRF (DHS, 2008b), with specific responsibility in the NDRF (FEMA, 2011a) for recovery, the strategies and approaches that govern the operation of responsible agencies in late-phase recovery have yet to be thoroughly evaluated for supporting and facilitating the requisite functions. The lack of coherent approaches will hinder decision-making deliberations and therefore the efforts associated with site cleanup and restoration (Chen and Tenforde, 2010; Eraker, 2004; GAO, 2009; Nisbit and Chen, 2014). Since society in general has little or no experience in addressing large-scale nuclear or radiological incidents, an evaluation of the relevancy and applicability of existing policies and approaches as they pertain to late-phase recovery issues is warranted. The national strategy for supporting such efforts is generally embedded in existing policies that have governed remediation activities over the last few decades.

Responsibility for responding to nuclear or radiological incidents is currently specified under the NRF. The framework identifies the key response principles, as well as the roles of officials that organize responses ranging from local to regional to national. The scope and responsibilities of federal support are further prescribed under the ESFs within the NRF. Fifteen support functions have been identified with responsible federal agencies for each. For the late-phase recovery issues, the primary responsibility falls under ESF #10 (Oil and Hazardous Materials Response) with EPA as the lead coordinating agency. For issues related to long-term cleanup, it is likely the effort also overlaps other support functions such as ESF #3 (Public Works and Engineering) (led by the U.S. Department of Defense (DOD)/Army Corps of Engineers), and ESF #14, (Long-Term Community Recovery) (lead by DHS/FEMA), and also other related functions. DHS remains as the coordinating agency and retains the overall incident management authority for all incidents under Homeland Security Presidential Directive 5 (HSPD, 2003).

Thus, under ESF #10, EPA is likely to use its current statutory mandate under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980) framework for cleanup activities following a nuclear or radiological incident, at least for initial investigation and data collection. This framework was created in 1980 to provide broad federal authority to respond to oil spills and other releases of hazardous substances that may threaten public health or the environment (EPA, 1990). It is uncertain how the AEA (1954) exemption will be applicable in some scenarios.

For cleaning up land contaminated with radioactive material and the environment, there are a number of policy-related issues that need to be addressed and resolved as part of the overall effort toward preparedness and response. These issues are discussed below:

1. Current policy for environmental cleanup needs to be carefully evaluated and updated to incorporate measures that address contamination issues under specific incident-related situations. As discussed, the likely response to environmental cleanup of areas contaminated by an incident is mandated through ESF #10 by means of the EPA current statutory mandate under CERCLA provisions. Thus, sufficiency and applicability of the response provisions will be important to address if the incident should occur today. The risk management approach in remediation of sites contaminated with radioactive material has been reviewed in depth in NCRP Report No. 146 (NCRP, 2004) where the regulatory provisions within current statutory requirements and regulations of federal agencies, including DOE, EPA, and NRC, are compared. For EPA, CERCLA provisions often offer the legal basis for the agency to address cleanup issues involving public areas. NCRP Report No. 146 compares the agencies' approach to risk management and specific, predetermined cleanup goals (or criteria) specified by their respective regulatory provisions, although it is uncertain how the AEA exemption in CERCLA may apply in certain response scenarios.

   Conventional cleanup processes are usually based on some predetermined regulatory limits (or limited risk range) for setting cleanup criteria and remediation procedures. This conventional approach is exemplified by the statutory cleanup approaches required by CERCLA (1980) cleanup activity, the DOE effort to remediate its former nuclear weapons complex, and the NRC effort to decommission its licensed facilities (NCRP, 2004). CERCLA, for example, requires meeting a preset cleanup criterion or risk goal together with prescribed procedures (*e.g.*, through a remedial investigation and feasibility study, together with 5 y of follow-up monitoring) (EPA, 2012). The optimization process, on the other hand, addresses many complex issues in addition to the long-term health risks usually emphasized by the conventional cleanup approach (*i.e.*, cleanup priorities addressed by optimization include many competing factors such as the local economy, infrastructure restoration, waste disposition, and stakeholder desires).

2. When there is widespread contamination with radioactive material, the populations will be subjected to a broad spectrum of exposure scenarios. The possibility of individuals receiving multiple exposures in affected areas challenges the conventional cleanup approach that constrains individual doses (or associated risks) to the pre-established limits or goals for one single contaminated site (and its associated exposure scenario). Consequently in situations with multiple exposure scenarios, collective dose should supplement the determination of cleanup priority in order to facilitate the long-term management of the contamination.
3. Widespread contamination will likely result in elevated radiation background levels compared with those before the incident occurred. Elevated background levels may not be limited to local contamination, but may include direct radiation or even skyshine from (*e.g.*, adjacent contaminated sites or contaminated objects such as trees in the affected zone). Again, the approach to cleanup will need to consider a broader context beyond the conventional process of addressing contamination of a single area. In addition, the possibility of recontamination by weathering effects (such as resuspension or runoffs from contaminated areas) or human activities following cleanup actions should be addressed.
4. The optimization process requires a holistic approach to addressing the overall issues surrounding the remediation and management effort. Where possible, a life-cycle analysis should be included. For example, although power washing contaminated building rooftops or walls may be inexpensive, its effectiveness in decontamination plus the generation of secondary waste should be weighed in evaluating the overall appropriateness of this technology. No single factor should serve as the only consideration for decision making without properly considering the overall merits (and any demerits) of a particular remediation option. An optimization process cannot be executed properly without

a comprehensive understanding and full resolution of all potential policy issues. Harmonizing and streamlining relevant policies is necessary to avoid inconsistencies or discrepancies that might lead to delays and inefficiencies, or result in a more costly cleanup effort. A comprehensive effort should be made to evaluate current statutory requirements to accommodate the needs that are specific to the cleanup effort in the long-term management strategy.

5. Relatively narrow risk ranges targeted by existing statutory cleanup requirements may limit consideration of a full range of remediation options available for areas with widespread contamination. The optimization approach, on the other hand, will allow an expedited approach to remediation while systematically reducing the potential risks through long-term management.
6. Potential stigma could be imposed on an extended area (such as a major metropolitan area or agricultural land) by declaring it as a statutory contaminated site (such as a CERCLA site), thereby adding to adverse effects from an incident.
7. Any major nuclear or radiological incident may cause unprecedented demands on the nation's resources and effort, and so care should be taken to ensure that timely recovery can be afforded by current response structure and meet the long-term needs of the affected community.
8. In anticipation of the large amount of waste to be generated in the remediation of contaminated areas following a major nuclear or radiological incident, it is important to evaluate the current policy on radioactive waste management approaches and practices to accommodate and facilitate effective cleanup operations. Large quantities of radioactive waste (mostly in the form of LLRW) will likely be generated from remediation of areas with widespread contamination (IAEA, 1988; 2006b; 2011a). Because radioactive materials could be spread across large public areas, much of the waste collected will likely contain very low activity levels. In addition, since some trace amounts of radionuclides can remain present in the environment long after an incident, it is inevitable that some level of contamination will be prevalent throughout the daily activities of the affected populations for years to come.
9. Handling and managing the radioactive waste will present several challenges to decision makers. The effort will involve proper characterization of waste and the evaluation

of the full range of disposition options, both within and beyond the current LLRW classification system in the United States, to determine optimal disposition actions. Since current waste management requirements are designed primarily for the operation of licensed facilities, they do not include waste generated from other incidents, such as a terrorist attack involving an RDD or IND. Accordingly, expanding the current regulatory definition of LLRW[7] to accommodate the development of appropriate and effective waste disposition options should be considered.

10. Currently, there is limited LLRW disposal capacity in the nation and the locations of these sites are usually remote, leading to prohibitively high disposal costs for large volumes of waste. Some incident scenarios may require consideration of disposal at other types of facilities that may be able to manage waste with low concentrations of radionuclides, such as EPA regulated landfills under the Resource Conservation and Recovery Act (RCRA, 1976) (CERCLA, 1980), Subtitle C (for hazardous waste) and Subtitle D (for municipal waste) landfills. In addition, efforts should be made to develop and apply appropriate concentration levels below which certain waste can be exempted from disposal requirements, as exemplified in the cleanup effort following the radioactive source incident in Goiânia, Brazil of 1987 (IAEA, 1988). Current policy on the disposal of LLRW needs to be carefully evaluated to accommodate such considerations (NA/NRC, 2002; NCRP, 2002a). Thus, it would be prudent to identify and resolve the related policy-related issues surrounding LLRW disposal as part of the planning strategy. These issues and options have been evaluated in the initial cleanup effort in Japan relative to the Fukushima Dai-ichi NPP accident (IAEA, 2011a).
11. Another challenge in remediating widespread contamination with radioactive materials involves the methods and technologies for reducing the total volume of radioactive

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[7] According to NRC (2013a), low-level waste is defined as “radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or byproduct material as defined in Section 11.2 (e) of the Atomic Energy Act (uranium and thorium tailings and waste).” This definition applies specifically to waste generated in a nuclear facility. For waste generated by an RDD- or IND-related incident on public property, a new, uniquely explicit definition would be required.

waste generated. When a large-area contamination incident occurs, new innovations and technologies for remediation will likely be developed and made available. Processes need to be put in place to allow timely evaluation of the available and appropriate decontamination technologies that would be best suited for the incident- and location-specific situation. Lists of appropriate cleanup options and plans for managing the radioactive waste generated should be the result of such activities and made available to stakeholders in the decision-making process. Where essential technologies may be needed, future plans should include investment in research endeavors for their development (Section 7.7).

12. To meet the need for communities to establish appropriate self-help programs after a catastrophic incident, it is necessary to evaluate and adjust the existing policies to accommodate these programs. In a major disaster, resources and assistance needed from the authorities may be either limited or delivered in an untimely manner. Such uncertainties may prompt citizens of the affected communities to embark on individual or local actions to alleviate the adverse situations encountered in their daily lives. To achieve a timely recovery of the community, citizens should be encouraged to provide their own assistance to meet their immediate needs, as described in the FEMA *Long-Term Community Recovery Planning Process: A Self-Help Guide* (FEMA, 2005). This process has been successful in bringing communities together to focus on their long-term recovery issues and needs and to develop projects and strategies to address those needs. The specific need for community volunteers and assistance has been important in previous nuclear incidents (IAEA, 1988; 2006a; 2011a). Following the Fukushima Dai-ichi NPP accident (IAEA, 2011b), substantial assistance from local governments, communities, and individuals were provided to the cleanup effort throughout the contaminated areas. Some of the efforts originated as spontaneous actions without specific guidance or support from the central government. It is advisable that national policies be developed and instituted to incorporate self-help programs into the overall response strategy for the late-phase recovery activities. Such guidance may include radiation monitoring of residences and community areas, monitoring of food and drinking water in the immediate surroundings, decontamination of

residences or community areas, and proper collection and disposal of contaminated debris or materials.

13. Other important policy issues to address in long-term cleanup strategies include property condemnation and compensation, economic assistance, and recovery of community infrastructure and facilities.

7.7 Research and Development

> Research to develop new technologies, methodologies, and strategies should be conducted to address the special issues and concerns for remediation of wide-area contamination with radioactive material.

Experience and knowledge has been gained over the past few decades from cleanup activities conducted under various statutory requirements (including the CERCLA cleanup activity, the DOE effort to remediate its former nuclear weapons complex, and the NRC effort to decommission its licensed facilities). However, as discussed earlier, significant differences exist between the conditions for which those policies were created and those that might be faced in present day or future scenarios, particularly those associated with wide-area contamination caused by major nuclear or radiological incidents. Thus, it is necessary to conduct research aimed at improving the efficiency and effectiveness of large-scale cleanup technologies, methodologies and strategies. Recommendations for research and development are listed below:

- Deployment of cleanup technologies needs to account for a potentially massive cleanup effort such as widespread contamination of several tens of city blocks or many square kilometers of farmland. Most existing technologies and strategies have been applied to manageable contaminated area sizes with recognized boundaries, and thus their applicability, efficacy, and cost-effectiveness are largely unknown for widespread contamination situations. For example, no decontamination technology has been applied within a large, heavily populated metropolitan area such as might occur following a large-area major nuclear or radiological incident. The availability and applicability of such technologies have not been well developed or documented. In addition, conventional technologies may be deficient in addressing emerging issues associated with widespread contamination. Examples include the technologies that have been considered in the cleanup efforts experienced after the Chernobyl nuclear reactor accident in 1986 (IAEA, 2006a) and also the more recent Fukushima Dai-ichi NPP accident in Japan in 2011 (IAEA/NEFW, 2011; NIES, 2012).

- It is important to recognize and address the interrelated issues associated with wide-area remediation. For example, since large quantities of radioactive waste may be generated in the remediation process, any deployed decontamination technology will need to evaluate and address this challenging consequence. Further, the evaluation should also consider the subsequent generation of secondary waste (such as liquid radioactive waste) that may accompany the decontamination process. Development of appropriate remediation technologies for widespread contamination with radioactive material should incorporate the life-cycle considerations discussed above (Section 7.6).
- Current knowledge on the migration and transport of radionuclides in the environment should be strengthened, particularly with regard to the modern urban environment. Extensive scientific investigation is needed to handle the interrelated "real-world" issues, rather than simply focusing on a single physical phenomenon. These efforts would include tracking:
  - movement of radionuclides in the environment (*e.g.*, from the streets to transportation systems to the drinking water or sewage systems in an urban environment);
  - continued propagation of radioactive contamination beyond the area of deposition; and
  - accumulation of radionuclides that might be encountered in an urban environment and that should be removed before reoccupation.

  In addition, further research is needed to address the potential ecological damage caused by radioactive contamination (Copplestone *et al.*, 2001; ICRP, 2009). A well-developed knowledge and information base keyed to a specific incident would greatly help to formulate a sound cleanup strategy and thereby facilitate a rapid recovery.
- Analyses should consider both short- and long-term strategies and consequences. Current cleanup efforts tend to focus on subsurface transport to mitigate the long-term contamination of groundwater from existing conditions (*e.g.*, subsurface contamination). However, the situation following an RDD or IND terrorist incident (as well as after a major nuclear reactor accident) would involve primarily aboveground contamination and subsequent transport of radionuclides in the

environment. Because of the relatively high mobility of many contaminants, factors that could influence redistribution of contamination are ground-to-air resuspension, particle-size distributions, human disturbance, and adverse weather conditions (*i.e.*, weather effects on the characteristics and transport of contaminants). Analysis of these factors would entail applications of, and possible changes to and expansion of current models of contaminant dispersion to characterize the possible exposure scenarios adequately. Depending on the half-lives of the radionuclides involved, consideration of long-term contamination may also include issues associated with groundwater contamination.

- Research that provides for a comprehensive socio-economic assessment for long-term recovery following a major nuclear or radiological incident should be initiated. Aside from the potential effect on human health, the potential economic losses and the possible recovery costs should be characterized (Eraker, 2004; FAS, 2002). An important DHS-supported research effort has been undertaken in this area (CRETE, 2012) but further assessments are clearly needed. Additionally, the potential psychological impact on society is another factor that has yet to be fully understood and characterized (Bromet, 2014; Eraker, 2004). Other gaps in understanding for which new research is needed include strategies addressing future land-use options, waste generation and disposal, appropriateness of available cleanup technologies and approaches, and public acceptability.
- The important decisions leading to a long-term cleanup strategy would necessarily be risk-informed and aimed at achieving optimization. Thus, a risk-informed approach to address long-term recovery should be established. According to DHS guidance (DHS, 2008a), the optimization process should include, “potential future land uses, technical feasibility, costs, cost-effectiveness, and public acceptability.” DHS guidance further states: “Broadly speaking, optimization is a flexible, multi-attribute decision process that seeks to weigh many factors.” While an RDD may be considered a “weapon of mass disruption,” the exact magnitude of its impact on society has yet to be fully assessed because of the large variation in possible scenarios (FAS, 2002). The potential impact of an IND explosion is even less certain (CRETE, 2012), although it would be of significantly greater magnitude than those of RDD incidents, causing many more casualties as well as widespread contamination. Likewise, other

incidents such as the NPP accidents that occurred in Chernobyl and Fukushima have caused unprecedented environmental and economic consequences (IAEA, 2004b; 2006a; IAEA/NEWF, 2011). It is essential to realize that highly inaccurate predictions and assessments of potential effects could lead to erroneous decisions that adversely influence nuclear terrorism preparedness (Harney, 2009). Long-term cleanup strategies will thus entail extensive input and evaluations in order to optimize site cleanup and restoration in the aftermath of any major nuclear or radiological incident. Lessons learned from past nuclear incidents reinforce the urgent need to develop a sound basis for applying the optimization processes in late-phase recovery from a major nuclear reactor accident or terrorist attack involving an RDD or IND.

- A robust information technology infrastructure should be developed to support and enhance decision making for the optimization process as discussed in Section 4.3.3 and illustrated in Figure 4.2. Past experiences following major nuclear incidents have identified a lack of information technology solutions. Methods to use and display data instantly need to be developed to support a response to an incident in the most effective and expedient manner. The enormous amount of information that will be collected for late-phase recovery will require the use of an effective information infrastructure designed to capture, store, manipulate, analyze, manage and present all the types of data gathered. The system should facilitate the dissemination of information and the engagement of stakeholders throughout the decision-making process. In particular, timely display of the relevant information will greatly facilitate the information exchange, including the use of such tools as developed for the geographic information system to produce maps depicting the evolving contamination situations over a large region. Such an infrastructural platform will be best developed before the occurrence of any incident so that it can be fully evaluated, tested and calibrated against potential scenarios and underlying site-specific conditions. Such an infrastructure can be maintained, updated and enhanced, and readily deployed to address the possible responses to the broad range of issues that will be encountered in late-phase decision making as discussed in this Report.

7.8 Continuous Adaptive Learning

To promote continuous and adaptive learning, a mechanism should be established to integrate new information and lessons learned from past incidents into the strategies for late-phase recovery.

Although there have been no large-scale terrorist incidents involving radioactive materials, important lessons have been learned from past incidents that affected populations and communities. Some of these include accidents at NPPs (*e.g.*, Fukushima Dai-Ichi, Japan, 2011, and Chernobyl, Ukraine, 1986) as well as those involving nuclear weapons materials (*e.g.*, transport accident at Palomares, Spain, 1966), and others involving the misappropriation of high-activity sources (*e.g.*, Goiânia, Brazil, 1987), all of which led to long-lasting and widespread environmental contamination with varying long-term consequences. The Fukushima Dai-ichi NPP accident presents a specific challenge to a modern society for which the late-phase recovery effort is still ongoing. Further, there have been serious nonradiological incidents caused by natural disasters that have required the development of long-term recovery strategies (*e.g.*, September 11 terrorist attacks of 2001 and Hurricane Katrina of 2005 in the United States). These incidents with both radiological and nonradiological origins collectively provide considerable information and lessons learned for inclusion in late-phase recovery planning for any future nuclear or radiological incident.

To promote continuous and adaptive learning, information from past incidents should be studied and incorporated into strategies to address any future incidents. Incidents in the past have revealed approaches that have succeeded or failed, and such knowledge is useful to dealing with future incidents. Since these incidents occurred over a 50 y period and at widely separated geographical locations (with wide-ranging cultural and political backgrounds), a concerted effort is required to fully understand and document the important attributes of each in a way that they can be incorporated into a successful response and long-term recovery action for future incidents. Furthermore, many of the lessons learned are common to more than one incident, thereby highlighting the need for their integration into generic recovery preparedness and a protocol system for future incidents.

As late-phase recovery strategies becomes more integrated into national, state and local government response plans (Section 7.2), so too should mechanisms for incorporating information and lessons learned and being learned from past incidents. This will promote continuous and adaptive learning. Emerging information may require changes to current understanding and legislation with regard to cleanup strategies. The ongoing recovery process in Japan with respect to the Fukushima Dai-ichi NPP accident (GOJ, 2011; 2012) will continue to generate relevant and useful information for others to benefit from in the years to come. Therefore, it is time for mechanisms to be put into place to capture and act on these experiences to guide future approaches to late-phase recovery. Such a learning process can be improved by enhancing internal coordination among federal agencies in United States and through continued international cooperation, as exemplified in the Chernobyl nuclear reactor (IAEA, 2006a; 2006b; 2006c) and Fukushima Dai-ichi NPP accidents (ANS, 2012; GOJ, 2011; 2012; Gonzalez *et al.*, 2013; IAEA, 2006a; 2006b; 2006c; ICRP, 2012; NDJ, 2012; WHO, 2012; 2013).

Appendix A

Lessons Learned from Historic Incidents

A.1 Introduction and the International Nuclear and Radiological Event Scale

Major nuclear or radiological accidents have been extremely rare and no significant radiological terrorism attack has occurred. However, the potential consequences of such incidents compel us to collect all available information from all possible sources to assist our preparedness effort. The most relevant and credible information can only be derived from past nuclear or radiological incidents with sequelae that address late-phase recovery issues. In addition, relevant information can be gathered from nonradiological incidents, such as those caused by natural disasters and conventional terrorist attacks. This appendix presents a series of case studies from which important lessons for late-phase recovery have been identified; they are illustrative rather than comprehensive, and have been used to inform the discussions in this Report and particularly to help develop the set of recommendations presented in Section 7. Evaluations of these incidents highlight some common issues that might be experienced by society if an incident should involve wide-area contamination from RDDs, INDs, or nuclear or radiological accidents.

> The INES has been developed to characterize the magnitude of incidents and serves as a tool for promptly communicating the safety significance of reported nuclear and radiological incidents and accidents to members of the public in consistent terms. It categorizes incidents *via* seven distinct severity levels ranging from the lowest level (Level 1: Anomaly) to the highest level (Level 7: Major Accident).

To help characterize and communicate nuclear or radiological incidents to members of the public in a consistent manner, IAEA, together with the Organization for Economic Cooperation and Development's Nuclear Energy Agency, developed the International Nuclear and Radiological Event Scale (INES) (IAEA, 2008). The INES was designed to offer a better understanding of the magnitude of the potential impact from nuclear or radiological incidents. Because such incidents can cause varying degrees of harm to humans as well as to the environment, the level of severity represents the magnitude of the potential impacts and therefore indicates the likely mitigation efforts required for late-phase recovery.

The INES also serves as a tool for promptly communicating the safety significance of reported nuclear and radiological incidents and accidents to members of the public in consistent terms. The INES categorizes incidents into seven distinct severity levels (Figure A.1) ranging from the lowest level (Level 1: Anomaly) to the highest level (Level 7: Major Accident); any incidents lower than Level 1 are designated as "Below Scale: No Safety Significance." The INES can be applied to any incident associated with nuclear facilities, as well as the transport, storage and use of radioactive material and radiation sources.

The severity scale for nuclear facilities has been based on three important factors: the impact on people and the environment, the impact on radiological barriers and control, and the impact on defense-in-depth (the latter two apply only to nuclear facilities). Accordingly, a large release of radioactive material with subsequent widespread contamination of the environment would register a severity scale of at least Level 5 or beyond, with the following consequence to the affected people and the environment (IAEA, 2008):

- Level 5: Accidents with Wider Consequences:
  - several deaths from radiation; and
  - limited release of radioactive material, likely to require implementation of some planned countermeasures.
- Level 6: Serious Accident:
  - significant release of radioactive material, likely to require planned countermeasures.
- Level 7: Major Accident:
  - major release of radioactive material with widespread health and environmental effects requiring planned and extended countermeasures.

For example, the cesium source accident in Goiânia in 1987 was designated as Level 5; the high-level radioactive tank accident at Kyshtym in 1957 was designated as Level 6; and the Chernobyl nuclear reactor accident in 1986 and the Fukushima Dai-ichi NPP

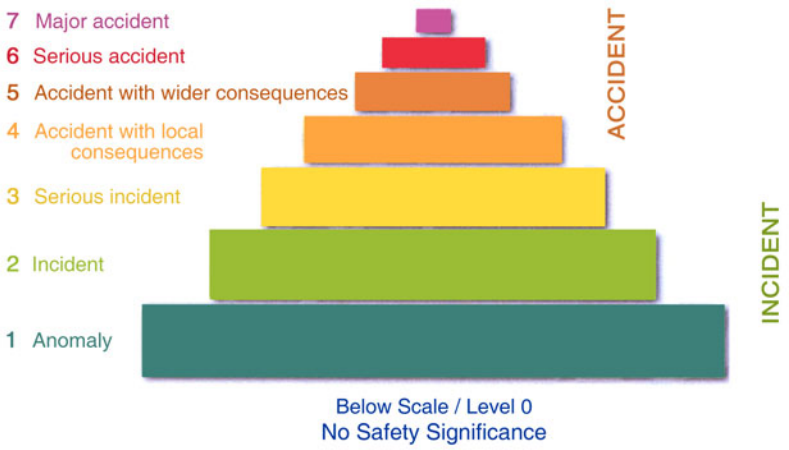

Fig. A.1. INES (IAEA, 2008).

accidents have both been designated as Level 7, the highest level on the INES.

The INES could be applied to radiological terrorist attacks. For example, a relatively small-scale RDD incident that affects one or more city blocks could be designated as Level 4 or below. A larger RDD incident could possibly reach Level 5 (Widespread Contamination) and an IND incident could reach Levels 6 or 7 (Potential for Causing Major Destruction) (Chen and Tenforde, 2010). Of course, IND incidents of much smaller scale could also occur and may result in only very localized damage and have a more limited impact.

A.2 Lessons from Nuclear or Radiological Incidents

The historic incidents described here illustrate the specific issues associated with wide-area contamination and long-term recovery. These include the following:

- nuclear and radiological facilities or sites;
- a limited-scale act of terrorism;
- atomic weapons testing or military activities; and
- recent exercises in the United States involving nuclear or radiological terrorism.

Where available information permits, cases are described in a common format that includes a description of the incident; a summary of impacts in terms of radiation exposures; contamination of land, foodstuffs and the environment; aspects of long-term recovery; and lessons learned. The studies are presented in a reverse chronological order, beginning with the accident at the Fukushima Dai-ichi NPP in Japan (ANS, 2012; GOJ, 2011; 2012; Gonzalez *et al.*, 2013; ICRP, 2012); recent exercises involving radiological terrorism scenarios are considered at the end of this appendix.

Four case examples of incidents at civilian facilities and sites were selected: Fukushima Dai-ichi NPP in Japan, Goiânia ^{137}Cs source accident in Brazil, Chernobyl nuclear reactor in Ukraine, and TMI accident in the United States. These incidents encompass a spectrum of impacts and approaches to recovery that span more than 30 y in different regions of the world. The rarity of nuclear or radiological terrorism means that there was only one published case study to consider, namely the poisoning of Alexander Litvinenko in London. (Another confirmed case was a thwarted terrorist attempt by Chechen rebels in Moscow, Russia in 1995).[8] Atomic weapons testing and military activities have led to several incidents, but not all are included as case studies. The chosen incidents offer the most learning points and include: the aircraft accident involving thermonuclear weapons near Palomares, Spain; the fire at the plutonium production factory at Windscale, United Kingdom; and U.S. nuclear weapons testing in the Marshall Islands. The accident at the plutonium production factory at Kyshtym, Russia (also known as the Mayak accident) occurred in the same year as the Windscale fire (1957) and has similar features but is less well documented (although efforts to investigate the consequences of the incident are ongoing); it is therefore not included here (although a brief description of the accident is provided in Section 3 to discuss the magnitude of the impact).

Exercising national preparedness for nuclear accidents is commonplace. In recent years there also have been exercises for response to terrorist RDD attacks [*e.g.*, DHS "top official" (TOPOFF) (DHS, 2007a; 2007b) exercises from 2003 to 2007, and Empire 09 in 2009]. However, the Liberty RadEx (LRE) exercise (EPA, 2010; 2011a) has been the first and only full-scale exercise in the United States to test post-emergency recovery planning. This exercise has been used to represent the status of preparedness for long-term recovery from a terrorist attack using an RDD.

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[8] A confirmed case of attempted nuclear terrorism was conducted in Russia on November 23, 1995, when Chechen separatists placed a bomb containing radioactive cesium in Moscow's Ismailovsky Park. The bomb was not detonated; instead, the rebels informed a television station of its location (Allison and Dillon, 2004).

A.2.1 *Nuclear Power Plant Accident at Fukushima, Japan (2011)*

A.2.1.1 *Description of the Incident*. An earthquake of magnitude 9.0 on the Richter Scale occurred on March 11, 2011 in the Pacific Ocean about ~130 km east of Sendai, Japan. The earthquake and the ensuing tsunami disabled all the external power supply sources to the six reactor units at the Fukushima Dai-ichi NPP, owned and operated by the Tokyo Electric Power Company (TEPCO). The cascading incidents eventually led to core melting in Units 1, 2 and 3 due to the loss of coolant, and also affected the spent nuclear fuel rods stored on-site. The accident caused an atmospheric release of radioactive materials, consisting mostly of ^{131}I and ^{137}Cs, with a total estimated activity of 0.77 EBq. Based on the estimate, the Japanese government eventually raised the provisional level to Level 7, the maximum on the INES (GOJ, 2011; 2012). This estimated release from the Fukushima accident represents ~10 % of the estimated quantity of 5.2 EBq total activity released from the Chernobyl nuclear reactor accident. Nevertheless, the contamination is deemed to be extensive.

A.2.1.2 *Summary of Impacts*. The natural disaster and ensuing nuclear accident has resulted in the most serious impacts ever to affect a modern society. The United Nations Environment Programme reported that, according to official Japanese government estimates, the triple disaster left 15,854 people dead and 3,155 missing as of March 2012. Hundreds of thousands of houses and other buildings were damaged and more than 400,000 people were displaced. With huge economic damage, this accident is considered not only tragic in terms of its human toll; it is the most economically devastating disaster in history (UNEP, 2012).

A.2.1.2.1 *Radiation exposures*. It was revealed (TEPCO, 2011) that, among the 6,700 personnel monitored, 88 received between 100 and 150 mSv effective dose, 14 between 150 and 200 mSv, three between 200 and 250 mSv, and six above 250 mSv. There was no known fatality associated with radiation exposures. A dose estimation was later conducted by WHO (2012) for the potential effects of contamination both in the affected areas in Japan and elsewhere in Japan as well as across the world. The study concluded the following regarding the average annual effective doses to individuals: 1 to 10 mSv in Fukushima prefecture; 0.1 to 10 mSv for prefectures neighboring Fukushima; and <0.01 mSv beyond the region. A more recent WHO (2013) report suggested that slight increases in lifetime cancer risk might occur in any heavily exposed subgroups of the population, although model estimates were based on conservative (high-sided) assumptions of exposure to hypothetically-exposed populations.

Shortly following the accident, the Japanese government quickly evacuated people within 20 km of the Fukushima Dai-ichi NPP and recommended in-house sheltering or voluntary evacuation between 20 and 30 km. Additional protective actions were taken shortly after the accident to distribute stable iodide tablets (or syrup for children) to minimize the potential thyroid doses due to ^{131}I uptake *via* both inhalation and ingestion pathways. It was reported in one survey that out of over 1,000 children who had their thyroids monitored for uptake of radioactive iodine, none had activities above the detectable level (Boice, 2011).

Although exposures to members of the public were minimal (Boice, 2011), there has been no official assessment of the collective dose to the affected populations thus far. Of the 195,345 residents who received screening in Fukushima prefecture as of May 31, 2011, no health effects attributable to radiation exposure were found (TEPCO, 2011).

A.2.1.2.2 *Contamination of land*. The emergency prompted an evacuation of about 140,000 residents from within the evacuation zone. The contamination affected a region estimated to be 8,000 km^2. In some areas, particularly along the northwest region from the Fukushima NPP, the ground contamination levels reached over 3 MBq m^{-2} and also reached elevated levels in other areas beyond the initial evacuation zone.

A.2.1.2.3 *Contamination of foodstuffs*. The initial atmospheric release following the accident indicated that some foodstuffs may have been contaminated beyond the provisional control limits prescribed by the Japanese government. As such, the government took immediate actions to monitor the environment, food and water supplies, and banned shipment and sales of contaminated foodstuffs and milk which exceeded the allowable standards. Such actions were taken both within and beyond the evacuation zone.

However, the issues on food contamination continued to linger several months after the accident. As late as July 19, 2011, the government imposed a further ban on beef produced from all areas of Fukushima prefecture after discovering contamination in the marketplaces of 2,300 Bq kg^{-1}, above the standard of 500 Bq kg^{-1}. The contamination was later attributed to contaminated feed (rice straw), which was found in Fukushima and the adjacent prefectures to contain as high as 690,000 Bq kg^{-1} of ^{137}Cs, versus the standard of 300 Bq kg^{-1} (Takada, 2011). A ban on mushrooms from another part of Fukushima was likewise introduced on July 23, 2011 due to elevated radiocesium levels. Yet another concern was seafood contamination; ^{134}Cs in seawater near the Fukushima

NPPs was discovered to be 30 times the allowable standards (Takada, 2011).

A.2.1.2.4 *Environmental contamination*. Contamination of the seawater from the atmospheric releases was detected early. Subsequent damage to the reactors and the effort to cool the reactors and spent fuel rods caused the leakage of highly contaminated water into the Pacific Ocean. A controlled release with an estimated amount of 0.15 TBq of activity was made into the sea in April 2011, by TEPCO (Japan News, 2011). This controlled release was conducted to make room for storing the highly radioactive water filling the Unit 2 reactor building, in an attempt to lower the risks to the workers at the plant. Some 300,000 Bq cm^{-3} of ^{131}I were reported along with high levels of ^{134}Cs and ^{137}Cs.

A few months following the Fukushima Dai-ichi nuclear accident, many local governments began to experience problems over how to handle waste containing radioactive cesium. It has been reported (Yomiuri Shimbun, 2011) that radioactive sludge was produced at the treatment plants, and the Japanese government currently aims to establish a new law to create a framework for its disposal. Without established guidance, the waste has to be stored temporarily on-site, since no landfills in the municipalities would accept such waste on a permanent basis.

There are concerns that the damaged plant at Fukushima is not equipped for the heavy rains and high winds typical of a typhoon season. Given the widespread contamination on the ground, it is likely that the contamination will be further distributed in the environment by natural phenomena. To address such a concern, there has been a focus on controlling the potential spread of radioactive leakage from the affected facilities.

A.2.1.3 *Summary of Long-Term Recovery.* While the recovery effort began shortly after the accident, extensive information on areal contamination became available only as more detailed data gathering and analyses began. Two IAEA reports, IAEA (2011a) and IAEA/NEFW (2011), summarized initial findings regarding the accident. The former, a fact-finding expert mission conducted shortly after the accident, focused on the safety and emergency aspects of the incident while the latter provided information on the initial cleanup effort. An investigation report was issued by the Fukushima Nuclear Accident Independent Investigation Commission of the National Diet of Japan (NDJ, 2012).

In October 2011, the Japanese government unveiled a decontamination plan for the eight prefectures that were heavily contaminated by the accident (Ishizuka and Harufumi, 2011). Under the plan the Japan central government will be responsible for decontaminating ~13,000 km^2 (or approximately the size of the State of Connecticut) under the newly developed standards, which include annual radiation levels above the ICRP "planned exposure" level of 1 mSv effective dose. In September 2011, the Diet of Japan approved the "Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011." The Act is the main instrument adopted to deal with the remediation program, and entered into force on January 1, 2012. The projected costs for the cleanup effort is expected to reach 1.2 trillion yen (or $15.6 billion), and the total effort may take many years or even decades, to accomplish (Ishizuka and Harufumi, 2011).

A.2.1.4 *Special Aspects of the Incident*. The Fukushima Dai-ichi NPP accident is a nuclear accident that was induced by an earthquake and subsequent tsunami. Its unique aspect is that the response to the nuclear accident was complicated by the preoccurrence of a major natural disaster. In addition, the effort to address remediation and long-term recovery has been underway only recently. Now characterized as only the second Level 7 nuclear incident on the INES, the Fukushima accident will require substantial effort for many years to come, and continue to provide valuable experience in large-area remediation.

A.2.1.5 *Lessons Learned*. Major lessons learned from the Fukushima Dai-ichi nuclear accident have been documented by IAEA (2011a; IAEA/NEFW, 2011), and also in an investigative report by NDJ (2012). ICRP (2012) and Gonzales *et al*. (2013) also published initial lessons learned pertaining to the ICRP system of radiological protection. The lessons, specifically relating to late-phase cleanup activities, can be summarized as follows:

- adhere to the principle of optimization as the main component of the remediation strategy which influences the net benefit of the remediation measures;
- enhance coordination among the central government, prefectural and municipal authorities;
- strengthen engagement with and cooperation among various stakeholder groups;
- carefully address the waste management issues pertaining to the radioactive contents, classification, management endpoint, and disposal infrastructure;

- adopt a risk-informed management approach to address long-term management issues;
- improve risk communication among the parties involved; and
- provide continued monitoring for the environment.

In addition, any action taken during the early or intermediate phase, such as removing debris, has some impact on late-phase recovery, especially in terms of such issues as waste disposal. As the remediation effort continues, it is anticipated that more lessons will be learned.

A.2.2 *Poisoning of Alexander Litvinenko with ^{210}Po in London (2006)*

On November 23, 2006, Alexander Litvinenko died in London as a result of poisoning with ^{210}Po, an alpha-particle emitter. The spread of radioactive contamination arising from the poisoning and developments leading up to it involved many locations in London. The potential for intakes of ^{210}Po from the contamination posed a public health risk and generated considerable public concern. The magnitude of the incident required a multi-agency response, including top-level government emergency response management arrangements (Croft *et al.*, 2008). The early phase continued into January 2007, with the recovery phase lasting until June 2007.

A.2.2.1 *Description of the Incident*. Alexander Litvinenko was an officer who served in the Soviet KGB and its Russian successor, the Federal Security Service. In 2000, he came to London with his family and was granted asylum in the United Kingdom in May of 2001, where he became a writer. On November 1, 2006, Litvinenko suddenly fell ill and was hospitalized in what was subsequently established as a case of poisoning with ^{210}Po. The events leading up to his poisoning and death were subjected to a full investigation.

Once ^{210}Po had been identified as the agent used, it was possible to reconstruct the time sequence of the incident as Scotland Yard detectives uncovered several polonium trails into and out of London. The Itsu Sushi Bar was contaminated in the first attempt at poisoning and the Millennium Hotel during the second attempt. Most of the contamination was located in the Westminster area of central London. Some 47 locations were checked for contamination, including hospitals, hotels, offices, restaurants, bars, cars, buses, and even aircraft. Of those 47 locations, 21 were found to have traces of polonium. At the peak of operations there were 70 monitoring staff working in shifts. A key observation was that the contamination was not uniformly distributed. Contamination found on hard surfaces was largely fixed (*i.e.*, not readily removable) and therefore not readily available to be taken into the body.

Polonium-210, which occurs naturally in the environment and has a relatively short physical half-life of 138 d, decays to a stable isotope of lead. For the levels of contamination that were found, this means that except in a few extreme instances, even if the contamination was left *in situ*, after 4 to 5 y there would be little or no further hazard. Polonium-210 is essentially a pure alpha-particle-emitting radionuclide. Due to the very short range of alpha particles (*i.e.*, less than a few tens of microns in soft tissue) ^{210}Po does not pose a hazard when external to the body. The only hazard is if the radionuclide enters the body *via* inhalation, ingestion, or contaminated wounds. It follows that detecting ^{210}Po on surfaces such as floors or furniture does not in and of itself mean that there is a risk to health: the ^{210}Po has to be unbound from physical surfaces and sufficiently mobile to be transferable into the body.

Some 618 people living in the United Kingdom were tested by the Health Protection Agency (HPA) to see whether they had been exposed to ^{210}Po. The urine tests showed that 137 had been exposed to ^{210}Po, 17 of them at levels which were not high enough to cause immediate health problems, but which could present a long-term health risk. This group included the widow of Mr. Litvinenko and a number of people who worked in the hotel's bar.

A.2.2.2 *Summary of Impacts*. Modeling techniques were used to estimate the range of potential radiation doses to people who were either present at the contaminated venues or in contact with other individuals potentially contaminated. Intakes of ^{210}Po into the body *via* inhalation, ingestion or wounds were considered for various objects and surfaces (*e.g.*, walls, doors, upholstery, crockery) contaminated either directly or through body fluids (*e.g.*, sweat, blood, urine). The potential radiological impact of the discharges of ^{210}Po to sewers from the two hospitals and from incineration of clinical waste was also considered as well as the implications of burial or cremation of the remains of Mr. Litvinenko.

HPA led the public health response. On November 25, 2006, following a risk assessment, HPA made a media request asking members of the public who were in identified contaminated locations within a specified period to contact a 24 h National Health Service helpline. To support this request, a questionnaire was developed to assist the collection of key information from callers; overall there were 3,837 calls to the helpline. Collection of 24 h urine samples was organized for those identified as most at risk, and urine samples from 752 people were processed and assessed: 86 results were greater than the reporting level but <1 mSv effective dose; 36 results were >1 mSv but <6 mSv; and 17 results were >6 mSv effective dose. Of the people in the highest dose group, 14 were staff and visitors at the Millennium Hotel bar, two were staff members from another hotel, and one was a family member caring for Mr. Litvinenko before he went to the hospital. The highest assessed effective dose (~100 mSv) was for the family member (Croft *et al.*, 2008).

Death from intakes of ^{210}Po occurs as a result of widespread damage to the organs and tissues of the reticulo-endothelial system, including red bone marrow. For lethal damage to red bone marrow (acute haematopoietic syndrome) from ^{210}Po, the median lethal dose is ~3 Gy absorbed dose. To deliver this level of dose requires a large intake of ^{210}Po (by activity), but only a very small amount by mass. Ingestion of 1 to 3 GBq of ^{210}Po, assuming 10 % absorption in the gastrointestinal tract, is likely to cause death within about three weeks of intake, consistent with the timing of the death of Mr. Litvinenko.

At doses below the multi-gray thresholds for the induction of acute effects that involve gross tissue damage, the risks of exposure are the possibilities of radiation-induced cancer and hereditary disease. Based on dose assessment from the urine samples, HPA (2007) calculated that for doses <6 mSv effective dose, any increase in the risk of cancer will be <0.03 %, which compares with the risk of dying of fatal cancer of ~25 % in the population as a whole. Because 0.03 % is a very small increase in risk, the HPA advised people that the dose received was of no concern. For those with doses ≥6 mSv effective dose, the results were reported as of some concern, requiring further follow-up. The highest assessed doses indicate possible increases in the risk of cancer of less than ~0.5 %.

Westminster City Council spent approximately £250,000 (approximately $400,000) on environmental health staff to close and clear sites, and the HPA, which checked more than 1,000 people and all 47 sites, spent approximately £2 million (approximately $3 million) on the investigation. There were other significant costs associated with the cleanup of properties and lost revenue for the periods of time when commercial venues were closed. For example, the Millennium Hotel bar, which closed on November 26, 2006, did not reopen until April 18, 2007, and the Itsu Sushi Bar, which closed on November 24, 2006, did not reopen until February 22, 2007. The total costs have not been published, but based on the thousands of phone calls received by the authorities, there was clearly public concern about potential exposure to radiation from ^{210}Po in London. There was also concern by the owner/occupiers of the contaminated restaurants, hotels and bars that their businesses would be adversely affected which resulted in pressure to cleanup venues that would not be justified on purely radiation protection grounds.

A.2.2.3 *Summary of Long-Term Recovery.* It was clear within the first day or so that the incident would have a significant recovery phase. The following long-term, late-phase issues were associated with the incident:

- derivation of criteria for the cleanup;
- provision of guidance on remediation requirements and waste management;
- prioritization of resources for actions including closure of venues, monitoring, remediation and communication; and
- development of a framework to ensure that each of the venues potentially contaminated by ^{210}Po were returned to a condition that is, or determined to already be safe for public use, taking into account their intended uses.

A.2.2.3.1 *Cleanup criteria*. HPA recommended a value of 10 Bq cm^{-2} as a reference level for fixed surface contamination with ^{210}Po (HPA, 2006). This value is based on conservative calculations to estimate levels of dose that might be received from exposure to contamination at this level. A number of scenarios were considered involving people of different ages engaged in a range of behaviors, from inhalation of resuspended material, direct entry of contamination into wounds, or ingestion of material. Based on these assessments, it is not expected that any individual would receive doses exceeding 1 mSv effective dose (*i.e.*, the United Kingdom annual dose limit for members of the public).

A.2.2.3.2 *Approach to environmental remediation and technology.* The key aspects of the approach were: a radiological survey to characterize the profile of the contamination, a remediation proposal, approval of proposal, remediation work in line with the approved proposal and preparation of the final report, and verification and clearance. The profiling, development of proposals and remediation work itself was carried out by specialist contractors. The proposals were approved by the relevant regulatory bodies. Finally, HPA carried out the assessment of the effectiveness of the remediation and made the recommendation that the location could be released for unrestricted use. A full description of the framework developed for dealing with remediation of contaminated venues is given in a report by Westminster City Council (WCC, 2007).

A.2.2.3.3 *Mobile contamination*. It was the mobile component of ^{210}Po that presented the radiological hazard and areas could not be declared safe for general access until that component was removed. Options for removal included wiping, washing and "bagging" of contaminated objects, followed by their removal to safe temporary storage to wait for appropriate decontamination or disposal. The removal of mobile contamination was carried out by specialists. On solid, nonporous surfaces like varnished wooden furniture and painted walls, a strong detergent called Decon-90® (Decon Laboratories Limited, East Sussex, United Kingdom), containing ~3 % potassium hydroxide, was used. Soft furnishings require special mention. For these items, it is more likely that apparently fixed contamination could become available for intake, particularly by children. Therefore, it was recommended that if contamination was detected on soft furnishings, it should be treated as potentially mobile. Either the area affected or the whole item should be bagged, removed, and taken to safe temporary storage to await disposal. If a contaminated furnishing had emotional value or historical significance, it was advised that the item could be suitably covered to prevent spread of contamination and then removed to safe storage until the activity of the radionuclides had decayed away.

A.2.2.3.4 *Fixed contamination*. Surfaces with fixed contamination >10 Bq m^{-2} were remediated. The form of remediation depended on a number of factors including the degree to which the contamination exceeded 10 Bq m^{-2}, the extent of the contamination (spots or widespread), and the wishes of key stakeholders, in particular, the owners of the premises/items. In some cases it was sufficient to provide additional reassurance that the contamination is truly fixed (*e.g.*, by applying a coat of paint, rather than decontaminating the surface). In other cases, particularly if the item was portable and of low value (both in terms of replacement cost and emotional value), the optimum remediation was simply to remove the item and dispose of it. Some porous surfaces posed problems because ^{210}Po had penetrated the surfaces of enamel-coated bathtubs or wash basins in certain London hotel rooms, so rather than try to dispose of whole bathtubs, the enamel was removed and then bagged and stored for disposal. In all cases, remediation was done by specialists. Where decontamination was carried out, the surface was remonitored to check both the residual level of contamination and to help ensure that no mobile contamination remained. One of the most contaminated venues, the Millennium Hotel, took 19 d to clean. Surfaces contaminated with fixed contamination ≤10 Bq m^{-2} did not require decontamination on health grounds. However, further remediation may have been carried out for commercial concerns or for reassurance.

A.2.2.3.5 *Waste management and disposal*. The ownership of the waste remained with the owner/occupant of the venue, who had to meet the costs for its transport, storage and disposal. Contractors undertaking remediation acted as consignors of the waste and had to prepare and suitably package the waste and arrange for transport, storage and disposal. The Environment Agency proposed three categories of waste. Category 1 waste with activity <0.37 Bq gm^{-1} was classified as uncontaminated and could be disposed of *via* the normal route appropriate for the material involved. Category 2 waste with activity ≥ 0.37 Bq gm^{-1} and <14.8 Bq gm^{-1} was classified as "exempt" radioactive material and such material could be disposed of in a suitable landfill with the full understanding and agreement of the landfill operator. Category 3 included all other contaminated material, which needed to be fully characterized. An emergency exemption order was used for Category 3 waste so that items could be disposed of without authorization. Most of the waste arising from the Litvinenko incident fell under Categories 1 and 2.

A.2.2.3.6 *Stakeholder involvement and communication*. HPA led the public health response and the local authority led the recovery program. A multi-agency Strategic Co-ordination Group was established by the London Metropolitan Police Service to provide the main interface to coordinate strategies for pursuing the police-led criminal investigation. The Strategic Co-ordination Group also addressed the health and safety of responders, community impact, media issues, and resources. It was clear that the incident would have a significant recovery phase so the group made an early decision to establish a subgroup; the Recovery Working Group, which was chaired by the Westminster City Council. The Recovery Working Group included all of the stakeholders likely to be involved in developing and implementing the recovery strategy. There was close collaboration between the Group and the owner/occupants of the contaminated venues.

Throughout the incident a balance in the level of communication had to be observed to preserve the confidential nature of the police investigation while at the same time being as open as possible with the media and members of the public. During the first few days and weeks, many interviews were given on radio and television. There were daily press statements, thousands of media calls, and websites to keep up-to-date with information (Croft *et al*., 2008).

A.2.2.4 *Special Aspects of the Incident*. The fatal poisoning of Alexander Litvinenko with ^{210}Po and the associated public health hazard from the spread of contamination to many locations across London was unprecedented. The incident was unexpected, very complex, and involved teamwork by multiple agencies. An enormous amount of effort was required in a short span of time to develop effective systems for distinguishing those individuals at the highest risk of significant intakes from the thousands of potentially exposed, collecting urine samples from them, measuring the ^{210}Po present, assessing their doses, and communicating the results. At the same time, monitoring resources had to be deployed to numerous locations identified by the police. Monitoring strategies and priorities had to be established quickly in conjunction with a framework for dealing with any contamination that was found. The consensus was that the response was very effective. It highlighted the strengths of existing emergency and recovery arrangements and the benefits from multiagency involvement in regular emergency exercises.

A.2.2.5 *Lessons Learned*

- pre-existing arrangements for recovery worked well, particularly because they were regularly exercised for multiple risk scenarios;
- engagement of stakeholders during the response phase and into recovery was important to the success of the remediation strategy;
- communication strategy was open and transparent (regularly provided updated information through a variety of media and this was sustained throughout the response phase and into recovery);
- acceptable cleanup criteria and a waste management strategy were developed at the time of the incident; and
- disposal options for the higher activity waste were not readily available; a better waste management strategy that included the identification of disposal routes before future incidents was recognized as an area that needed improvement.

A.2.3 *Cesium-137 Source Accident, Goiânia, Brazil (1987)*

A.2.3.1 *Description of the Incident*. This incident began on September 13, 1987. It involved the inadvertent scavenging of a radioactive medical teletherapy source [*i.e.*, radiotherapy using external radiation beams (containing ^{137}Cs in the form of cesium chloride)] from an abandoned clinic near Goiânia, Brazil. Since the incident was not recognized for several days, it continued over a two-week period until serious health effects were discovered. Radioactive contamination was initially spread locally by individuals inadvertently exposed to the broken source, and later became more widely spread to some parts of the city resulting in extensive contamination that required a large-scale remediation effort. The contamination spread over ~1 km^2 due to human activities, heavy rainfalls, wind, and traffic. The subsequent cleanup effort extended over several months, largely due to the lack of preparedness and specific guidance in responding to the unprecedented incident. A total of 44 TBq of ^{137}Cs was accounted for through the cleanup effort [out of a total of 51 TBq in the original cesium chloride source].

Actions taken to clean up the contamination were conducted in two phases: (1) urgent actions to bring all potential sources of contamination under control (mostly completed by October 3, 1987); and (2) remedial actions aimed to restore normal living conditions lasted until March 1988.

A.2.3.2 *Summary of Impacts*. The incident resulted in four deaths due to acute radiation exposure and one person required amputation of an arm due to severe skin burns. One hundred and twenty-nine people were found to have measurable bodily contamination, with 21 requiring hospitalization (Eisenbud and Gesell, 1997). The estimated collective effective doses to the population were 56.3 person-Sv from external exposures and 3.7 person-Sv from internal exposures (ICRP, 2009).

In addition, 85 houses were found to have significant contamination, and 200 individuals were evacuated from 41 of them. In all, 3,500 m^3 of waste, stored at a temporary waste storage site located ~20 km away from Goiânia, was generated through the cleanup effort.

Other than the health impacts, residents also suffered from significant economic and social stigma that lasted for an extended period. It was reported that the entire agricultural production of Brazil fell by 50 % within the first two weeks and prices of manufactured goods dropped by 40 %. Travel restrictions to other states were encountered by residents of the entire state of Goiânia, and sometimes certificates of noncontamination were requested of people and goods from the affected region.

Although the total final cost for the cleanup effort is not known, it is believed to be substantial (IAEA, 1988).

A.2.3.3 *Summary of Long-Term Recovery.* The cleanup effort was subject to strong political and public pressure. It was reported that action levels for decontamination were set substantially lower than would have been the case from an optimization process (*i.e.*, about one-fifth of the intervention levels recommended by IAEA and ICRP); the target dose level was set to be applicable to planned exposures rather than to an existing exposure (accident recovery) situation. For decontamination of houses, vacuum cleaning was used for inside and high-pressure water jets were used for outside. In addition, chemical decontamination agents were used. The *ad hoc* contamination and dose limits (Eisenbud and Gesell, 1997) were:

General surface contamination	3.7 Bq cm^{-2}
Gamma rays in houses	0.5 μGy h^{-1}
Gamma rays outdoors	1 μGy h^{-1}
Contamination on fruits	650 Bq kg^{-1}

Waste was sorted into three categories (IAEA, 1988):

Nonradioactive	<74 kBq kg^{-1}
Low level	<2 mSv h^{-1}
Medium level	2 mSv h^{-1} to <20 mSv h^{-1}

Overall, a total of 3,500 m^3 waste was stored at the temporary waste storage site which had a total capacity of 4,000 to 5,000 m^3.

Due to migration of radioactive cesium in soil and the environment, additional remediation was deemed necessary for the long-term recovery, mainly for contaminated houses, gardens and streets (ICRP, 2009). Due to lack of existing regulation, the approach to long-term remediation was based on a dose limit of 5 mSv effective dose for the first year and an average of 1 mSv y^{-1} effective dose for the subsequent years, considering the weathering and physical decay of ^{137}Cs over 70 y (ICRP, 2009).

Long-term monitoring was conducted for many years. The monitoring program came to an end in 1996 due to the negative public perception (*i.e.*, the possible long-lasting stigma associated with radiation contamination) which led to removal of the thermoluminescent dosimeters placed in monitored houses, or denial of access to the devices (ICRP, 2009). Limited follow-up remediation was conducted in 2004 resulting in the detection of elevated radiation levels in some "hot spots."

A.2.3.4 *Special Aspects of the Incident*. The Goiânia incident represents a major radiological incident that was related to a discarded or "orphan" radiological source. The incident attracted international attention that called for better control of high-activity radiological sources used in medical or industrial applications. Based on the magnitude of the incident it has been categorized at INES Level 5 (IAEA, 2008).

A.2.3.5 *Lessons Learned*. The lessons learned from the Goiânia incident have been well documented (IAEA, 1988). Some of these regarding remediation and long-term recovery are:

- lack of preparedness affected the success of the response and recovery;
- lack of a communication strategy led to loss of public trust and stigmatization of the affected population and area;
- lack of an adequate system of public information dissemination hindered timely release of critical messages and public understanding of the incident and preparedness;
- lack of an adequate system of social and psychological support following the incident exacerbated the overall health effects associated with the accident;
- lack of an expedient decision-making process for accommodating the temporary waste disposal contributed to the delay in remediation and further contributed to the dispersion of radioactive contamination in the environment; and
- lack of an organizational hierarchy with clear delineation of responsibility in the decision-making process contributed to ineffective remediation actions.

A.2.4 *Chernobyl Nuclear Reactor Accident (1986)*

The accident site is located in present-day northern Ukraine, some 20 km south of the border with Belarus and 140 km west of the border with the Russian Federation.

A.2.4.1 *Description of the Incident*. The accident occurred on April 26, 1986 during an experimental test of the electrical control system when the reactor was being shut down for routine maintenance. The operators, in violation of safety regulations, had switched off important control systems and allowed the reactor to reach unstable low-power conditions. A sudden uncontrollable power surge caused a steam explosion that ruptured the reactor vessel, allowing further violent fuel-steam interactions that destroyed the reactor core and severely damaged the reactor building. Subsequently, an intense graphite fire burned for 10 d. Under those conditions, large releases of radioactive materials resulted (UNSCEAR, 2008).

A.2.4.1.1 *Incident scenario*. The accident caused the largest uncontrolled radioactive release to the environment ever recorded for a civilian operation; large quantities of radioactive materials were released into the air for ~10 d. Most of the radionuclides released in large amounts (in terms of activity) had short half-lives; radionuclides of longer half-life were generally released only in small amounts. The most up-to-date estimates of the amounts released have been published by UNSCEAR (2008). From the radiological point of view, ^{131}I and ^{137}Cs were the more important radionuclides released. The releases of ^{131}I and ^{137}Cs were estimated to have been ~1,760 and 85 PBq, respectively. The deposited material consisted of "hot particles" in the near zone and more homogeneously distributed radioactive material widely dispersed into the far zone.

A.2.4.1.2 *Radioactive contamination*. The radioactive gases and particles dispersed over the entire northern hemisphere in a complex pattern. Owing to the emergent situation and the short half-life of ^{131}I, few reliable measurements of the pattern of radionuclide deposition were made. Three main areas of the former Soviet Union comprising 150,000 km^2 and more than five million inhabitants were classified as contaminated (arbitrarily defined as areas where ^{137}Cs levels in soil were >37 kBq m^{-2}). Outside the former Soviet Union, other large areas of Europe were also subjected to deposition of radioactive material (45,000 km^2 had ^{137}Cs deposition levels ranging from 37 to 200 kBq m^{-2}). The area classified as contaminated is slowly decreasing as ^{137}Cs decays away.

A.2.4.1.3 *Environmental transport*. The environmental behavior of the deposited radionuclides depends on their physical and chemical characteristics, the type of deposition (*i.e.*, wet or dry), and the characteristics of the environment. For short-lived ^{131}I, the main pathway of human exposure was *via* the transfer of deposited material on pasture grass to cow's milk. Within weeks, the very high initial concentrations became negligible because of radioactive decay and other physical and biological processes. For the long-lived radionuclides and ^{137}Cs in particular, the long-term transfer processes in the environment have been important in maintaining availability for root uptake. Levels in food depend not only on deposition pattern but also on factors such as soil type and agricultural practices. The uptake and retention of ^{137}Cs has generally been much higher in semi-natural ecosystems than in agricultural ecosystems, and the clearance from forest ecosystems is extremely slow. The highest levels in foodstuffs continue to be in mushrooms, berries, game and reindeer.

Levels of radionuclides in rivers and lakes directly after the accident fell rapidly and are now generally low in water used for drinking and irrigation, although ^{137}Cs in the water and fish of some closed lakes have only slowly fallen. Levels in seawater and marine fish were much lower than in freshwater systems.

Deposition of radioactive material in inhabited areas has contributed to external exposure of the inhabitants. The behavior of the deposited material depended initially on whether there was wet or dry deposition and on the characteristics of the buildings. The external dose rates have fallen with time because of radioactive decay and weathering, and in most places are now at pre-accident levels.

A.2.4.1.4 *Affected populations and the area*. In the countries of the former Soviet Union, the prevailing food production system at the time of the accident consisted of two types: large collective farms and small private farms. Collective farms routinely used land rotation combined with plowing and fertilization to improve productivity. In contrast, traditional small private farms seldom applied artificial fertilizers and often used animal manure for improving yield. Private farms had one or a few cows, and milk was produced mainly for family consumption.

In western Europe, the areas affected by the Chernobyl nuclear reactor accident have poor quality soils that were used extensively for agriculture, primarily for grazing cattle, sheep, goats and reindeer. Areas with poor soils include alpine meadows and upland regions in western and northern Europe with organic soils. High uptake of radiocesium in plants growing in these poor soils has contributed to a persistent contamination problem in animal production in Scandinavia and the United Kingdom.

A.2.4.2 *Summary of Impacts*. The released radionuclides that caused exposure of individuals were mainly ^{131}I, ^{134}Cs, and ^{137}Cs. Iodine-131 has a short half-life (8 d), but it can be transferred to humans relatively rapidly from the air and through consumption of contaminated milk and leafy vegetables. Iodine concentrates in the thyroid gland, and radiation doses are usually higher for infants and children due to higher consumption of dairy products and smaller mass of the thyroid gland. The radioisotopes of cesium have relatively longer half-lives (2 y for ^{134}Cs and 30 y for ^{137}Cs) and cause longer-term exposures through the ingestion pathway and through external exposure from their deposition on the ground.

Average effective doses to those persons most affected by the accident were assessed to be ~120 mSv for 530 recovery operation workers, 30 mSv for 115,000 evacuated people, and 9 mSv during the first two decades after the accident to those who continued to reside in contaminated areas. Maximum individual values of the dose may be higher by an order of magnitude or more. Outside Belarus, Ukraine, and the Russian Federation, the average national doses in other European countries affected by the accident were <1 mSv effective dose in the first year.

A.2.4.2.1 *Health effects*. The Chernobyl nuclear reactor accident caused severe radiation effects almost immediately among the emergency workers. Of 600 workers at the site during the morning of April 26, 1986, 134 received high doses (0.8 to 16 Gy whole-body absorbed dose) and suffered radiation-induced illnesses. Of these workers, 28 died in the first three months, most of whom had high radiation exposures combined with conventional trauma such as thermal burns. Another 19 died from 1987 through 2004 of various causes not necessarily related to radiation exposure. In the first few years after the accident, many of the emergency workers developed radiation-induced cataracts, and skin injuries from cutaneous radiation exposure (radiation burns) also manifested.

Since the Chernobyl nuclear reactor accident a substantial increase in thyroid cancer incidence has occurred among those exposed as children or adolescents in Belarus, Ukraine, and the four most affected regions in the Russian Federation. Among those under 18 y of age in 1986, 6,848 cases of thyroid cancer were reported between 1991 and 2005. Evidence (Cardis *et al*., 1995) has emerged that iodine deficiency might have increased the risk of thyroid cancer among those exposed to radioactive iodines from the accident. Although there is minimal evidence thus far of increased thyroid cancer incidence among those exposed as adults in the general population.

A.2.4.2.2 *Cleanup costs*. The effects of the accident have been devastating to the agrarian economies of Belarus, Ukraine and Russia. Some 2.6×10^6 km^2 of agricultural land have been affected. In Belarus, which received the greatest amount of fallout, the government has estimated that the 30 y program required to rehabilitate these areas will cost $235 billion, which is 32 times the nation's entire budget in the year of the accident. Consequently, that republic experienced the most serious of the health and economic consequences of any region (Eisenbud and Gesell, 1997). In Norway, it has been estimated that the various countermeasures in animal production during the first 10 y has cost some $70 million (Tveten *et al*., 1998).

A.2.4.2.3 *Psychological and other effects*. The Chernobyl nuclear reactor accident is known to have had major effects that are not related to radiation dose. These effects include those known to be brought on by distress and anxiety about the future, as well as increased levels of depression leading to changes in diet, smoking habits, alcohol consumption, and other lifestyle factors (UNSCEAR, 2008). In addition, the accident caused other long-term changes in the lives of the people living in the contaminated areas, since the measures intended to limit radiation doses included resettlement, changes in food supplies, and restrictions on the activities of families and individuals. Their circumstances were exacerbated by severe economic hardship, the exodus of skilled workers, the lack of social services, and the prevalent misconceptions and myths regarding health risks (IAEA, 2005a; 2005b).

A.2.4.3 *Summary of Long-Term Recovery.* The Chernobyl nuclear reactor accident registered the worst consequences and lingering impact on the affected regions both in Russia and a large portion of Europe in part due to the operations of the former Soviet regime that were conducted in secrecy and mismanagement of the crisis. Populations in the region were not notified or informed in a timely manner, resulting in delay in evacuation. The several thousands of childhood thyroid cancers could easily have been avoided if preventive measures were promptly implemented.

It was through the extensive international collaborative effort, such as coordinated by IAEA through the Chernobyl Forum and other activities (IAEA, 2005a; 2005b), that there have been concerted international endeavors to aid in the recovery from the incident. The Chernobyl Shelter Fund (EBRD, 2000), established in 1997 at the twenty-third G8 (group of eight largest industrialized democracies: Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States) summit in Denver, endeavors to finance the Shelter Implementation Plan aimed at stabilizing the hastily-built sarcophagus with the construction of a new safe confinement that will transform the site into an ecologically safe condition. The United Nations Development Programme launched a project in 2003 called the Chernobyl Recovery and Development Programme for the recovery of the affected areas. The goal is to support the Ukraine government in mitigating the long-term social, economic, and ecological consequences of the Chernobyl nuclear reactor accident. Additional efforts are devoted to monitoring the long-term health effects of the accident. The International Project on the Health Effects of the Chernobyl Accident was created to explore the incidence of health problems due to radiation exposure.

A.2.4.3.1 *Late-phase recovery issues.* Principal late-phase recovery issues have been associated with providing the affected populations with protection against the potential health consequences of radiation and creating sustainable living conditions, including respectable lifestyles and livelihoods. These issues have resulted in complex situations that could not be managed by radiation protection considerations alone, and so actions needed to address all relevant dimensions such as health, environmental, economic, social, psychological, cultural, ethical and political. Of particular relevance in the Chernobyl context were the provisions of radiation monitoring and health surveillance, and management of contaminated foodstuffs and other commodities.

The key objectives of the radiation monitoring system were to assess current levels of human exposure (both internal and external) and environmental levels of contamination, and allow the prediction of their evolution in the future. In practice, the monitoring system has provided measurements of ambient dose rates, concentrations of radionuclides in foodstuffs and the environment, and whole-body contamination of individuals. The monitoring system has made use of accredited laboratories at both the local and national level, enhancing confidence in the measurement data.

It has been essential for concerned individuals to receive general information on the exposure situation and the means of reducing their doses. Due to the large variation in individual exposure according to lifestyles, individual monitoring has been important. Furthermore, given the uncertainties about future potential health effects, long-term health surveillance has evolved in the affected areas.

The management of contaminated foodstuffs and other commodities produced in the contaminated areas presented a particularly difficult problem. The Chernobyl nuclear reactor accident highlighted that disruption to the local economy through the placement of restrictions on the sale of contaminated foodstuffs, and the loss of market share as a result of consumer preferences or through the provision of uncontaminated food, may not be warranted. Such decisions must be taken in close cooperation with local stakeholders, as was the case in Norway with reindeer meat produced by the Sami population. To avoid condemnation of 85 % of the total national reindeer population and to maintain a meaningful business base for the reindeer herders, as well as Sami culture and lifestyle, the intervention limit for radiocesium in reindeer meat was increased in autumn 1986 to 6,000 Bq kg^{-1} (this limit was also applied to wild freshwater fish and game). This level was justified by the low average consumption of these products by the general Norwegian population. As the situation improved, the intervention limit for reindeer meat was reduced to 3,000 Bq kg^{-1} in 1994.

A.2.4.3.2 *Cleanup criteria: Belarus, Russia and Ukraine*. The long-term contamination of the affected areas was a permanent concern for the population as far as their health was concerned because of uncertainty about protracted exposure. This concern prompted the governments of Belarus, Russia and Ukraine to expand and adopt laws in the early 1990s in an attempt to organize radiation monitoring and surveillance and to improve living conditions. The objective of these laws was to address long-term issues through a series of national countermeasures and compensation schemes based on radiation protection criteria. Rehabilitation programs in the early 1990s relied on further restrictions on living in contaminated areas (mandatory or voluntary relocation) and on strictly controlling the level of contamination in foodstuffs and the whole-body contamination of individuals. In 2001, a law was passed that stipulated that protective measures must be implemented if the average exposure of the population exceeds 1 mSv y^{-1} effective dose. As far as the control of foodstuffs is concerned, authorities adopted a pragmatic approach by reducing the concentration criteria as the situation improved.

A.2.4.3.3 *Cleanup criteria: Norway.* The Norwegian radiation protection criteria were based on the recommendations of ICRP concerning exposure to members of the public, with 5 mSv effective dose as the maximum dose in the first year after the accident and 1 mSv y^{-1} effective dose in subsequent years. A range of measures were needed to comply with these criteria, which reduced the average ingestion dose to reindeer herders by approximately 10-fold.

A.2.4.4 *Approach to Environmental Remediation and Technology*

A.2.4.4.1 *Inhabited areas.* Analysis of the contributors to external dose for different population groups revealed that a significant fraction of the dose came from radionuclides in the soil and on coated surfaces like asphalt. Large-scale decontamination of settlements was performed in the years 1986 to 1989 in cities and villages of the former Soviet Union with high levels of activity. Decontamination activities were usually performed usually by military personnel and included removal of contaminated soil, cleaning and washing of roads and washing of buildings with water or special solutions. Particular attention was paid to nurseries, schools, hospitals, and other buildings frequented by a large number of people. Depending on the decontamination techniques used, the dose rate was reduced by a factor of 1.5 to 5, but the high cost of these activities hindered their complete application. Because of this, the reduction in annual external dose was ~10 to 20 % for the average population, and ranged from ~30 % for children attending nursery and school to <10 % for outdoor workers.

A.2.4.4.2 *Food production systems.* The implementation of agricultural countermeasures after the Chernobyl nuclear reactor accident has been extensive, both in the affected countries of the former Soviet Union and in western Europe. The main goal of the agricultural countermeasures was adequate production of food products with activity of radionuclides below action levels. Many countermeasures were used extensively in the first few years after the accident and their application continues today. Since 1987, high-activity concentrations in agricultural products have been only observed in animal products; application of countermeasures aimed at lowering the activity concentrations of ^{137}Cs in milk and meat was the key focus of the remediation strategy for intensive agriculture. The strategy included treatment of the land used for fodder crops by enhanced fertilization and cultivation changes, clean feeding, and the application of cesium binders to animals and/or their feed. The maximum dose-reduction effect due to countermeasure application was achieved in the period 1986 through 1992. Thereafter, due to financial constraints in the mid-1990s, the use of agricultural countermeasures was drastically reduced.

In extensive systems, such as upland grazed areas in western Europe, the most commonly used countermeasures for free-ranging animals has been clean feeding, administration of cesium binders, monitoring of live animals, management restrictions, and changes in slaughter times. The application of long-term countermeasures has been most extensive in Norway, Sweden, and the United Kingdom.

A.2.4.4.3 *Forest ecosystems.* Prior to the Chernobyl nuclear reactor accident, countermeasures to offset doses due to large-scale contamination of forests had not been developed. Following the accident, simple measures were implemented to protect people residing in the forest and using forest products: restricted access; restricted gathering of firewood and food products such as game, berries and mushrooms; and alteration of hunting practices.

A.2.4.4.4 *Aquatic ecosystems.* Other than restrictions on the consumption of fresh-water fish from some closed lake systems in Scandinavia and Germany, countermeasures have not been required in the late phase.

A.2.4.5 *Waste Management and Disposal.* In the Chernobyl area, where great amounts of radioactive waste had to be disposed of very quickly at the initial stage when no final disposal sites or facilities were yet available, the waste was stored in surface mounds near the removal sites. The storage sites were located far from water systems and their catchment areas. The bottoms of the waste mounds were lined to prevent the run-off of liquids. The waste, which in addition to the contaminated earth, contained large amounts of vegetation and other organics, was collected in mounds with bulldozers. The mounds were first covered with a polyethylene film and then with clean earth. As the zone was closed off, a ditch was dug around it and warning signs were posted (IAEA, 1992).

In the Chernobyl area, a burial method known as semi-cavity/semi-mound was used in the final disposal of low- and intermediate-level waste. This method allowed >10,000 m^3 of waste to be disposed of in one large trench. The bottom and the walls of the trench were lined with clay, with the clay layer at the bottom 1 m thick. The waste was covered and leveled with a 0.6 m thick layer of native soil, on top of which was spread a 0.5 m thick clay layer. A 1 m thick layer of native soil was applied as an erosion barrier. The waters were directed around the trench, and each trench was equipped with a sampling well. The disposal site was fenced off and illuminated (IAEA, 1992).

A.2.4.6 *Stakeholder Involvement and Communication*. In the late 1990s new approaches were tried to enable the population to become directly involved in the management of the radiological situation. These new approaches demonstrated that the direct involvement of local stakeholders in the day-to-day management of a radiological situation is feasible and highlighted the potential for implementing many protective actions in day-to-day life in addition to the collective actions taken by the authorities. These approaches also demonstrated that to be sustainable, management of a radiological situation by stakeholders needs to rely on a dynamic of economic development focused primarily on individual initiatives of the local people in partnership with national and international institutions and organizations.

The focus on local competence and direct involvement of the affected population in countermeasure application and monitoring in Norway was a result of both the request from the population in the contaminated areas, and the recognition by the central authorities that the local food producers had local knowledge of importance for everyday management of the contamination.

A.2.4.7 *Lessons Learned*

- In the long term, the exposure of people living and working in contaminated areas is driven by individual behavior that calls for an individual approach to control the radiological situation. Provision of long-term monitoring and health surveillance supports the means by which individuals can reduce their doses.

- Widespread radioactive contamination had a lasting and significant psychological impact on the population that was partly attributable to a culture of secrecy and inadequate communication.
- Evolution of an optimization process based not only on radiation protection criteria but also (*e.g.*, on economic, social, psychological and cultural factors) was shown to lead to sustainable living conditions.
- Involvement of stakeholders in the day-to-day management of the radiological situation is feasible and encourages individuals to undertake self-help protective actions to further reduce their doses.
- When selecting intervention levels for food after an incident, it is important to adopt a flexible approach that considers the protection of livelihoods of vulnerable populations. Therefore, it is conceivable that intervention levels for certain foodstuffs may increase for a period of time.
- The presence of long-lasting contamination in a wide range of environments across Europe provided numerous opportunities for research and development on all aspects of cleanup that have since found application elsewhere (*e.g.*, in Japan, following the accident at the Fukushima Dai-ichi NPP).

A.2.5 *Three Mile Island Nuclear Accident in Dauphin County, Pennsylvania (1979)*

A.2.5.1 *Description of the Incident*. The accident at the TMI Unit 2 Reactor on March 28, 1979 was caused by operator error that led to the loss of reactor coolant, thereby leading to an estimated 50 % melting of the reactor core. The accident is considered the worst ever in the U.S. commercial nuclear power industry. It released ~4.81 TBq of radioactive gases (*i.e.*, relatively harmless noble gases) but only 740 GBq of ^{131}I to the environment. The incident has been designated as an INES Level 5 (Accident with Wider Consequences) (IAEA, 1988). As a precautionary measure, pregnant women and preschool-age children within a ~8 km radius of the TMI facility were advised to evacuate, and about 140,000 (or 52 %) residents within ~32 km voluntarily evacuated within days. Radioactive contamination was largely limited to the facility and its confines; the off-site releases (mainly noble gases and limited amounts of particulates) did not lead to any long-term contamination.

A.2.5.2 *Summary of Impacts*. The accident resulted in an estimated off-site population dose from 16 to 53 person-Sv collective effective dose equivalent, with the most credible being 33 person-Sv

(Eisenbud and Gesell, 1997), or an estimated one to two additional lifetime fatal cancer cases.

The response to the accident raised several issues:

- There were serious communication issues among the government agencies (*i.e.*, NRC and the Commonwealth of Pennsylvania), the owner of the power plant (General Public Utilities Corporation and Metropolitan Edison), and members of the public. The lack of well-coordinated communication and timely dissemination of accurate information led to general mistrust by members of the public.
- The public mistrust added to a series of difficulties in the recovery action, including the controlled discharge of noble gases to the atmosphere, release of treated wastewater into the Susquehanna River, and delay of inspection of the damaged reactor core upon the release of accumulated radioactive krypton gases from the reactor building (Eisenbud and Gesell, 1997).
- The lack of trust also contributed to the overall cost of cleanup.
- The psychological effects remained as the major impact to the society. The incident hindered further development of commercial nuclear power in the United States.

Although the accident did not cause any significant impact on people or the environment due to off-site releases, it was designated as an INES Level 5 as it did lead to significant damage to the reactor core. Since there was insignificant contamination to public land as a result, the recovery activity was limited largely to the cleanup of the facility itself, which took several years and cost about $975 million (Eisenbud and Gesell, 1997).

A.2.5.3 *Summary of Long-Term Recovery.* Since there was no off-site contamination associated with the accident, all physical recovery efforts were related to the decontamination and decommissioning of the damaged reactor. The sociopolitical ramifications proved to be among the primary long-term issues following the incident. The psychological trauma was the only observed health effect associated with the accident (Eisenbud and Gesell, 1997). In addition, the accident led to a fundamental change in the emergency response approach relative to nuclear incidents in the United States, and specifically to the development of the PAGs which address radiological criteria for response to nuclear incidents including late-phase issues (EPA, 1992).

A.2.5.4 *Special Aspects of the Incident*. The TMI nuclear accident represents the first major nuclear incident in the commercial U.S. nuclear history, which profoundly influenced the regulatory approach to nuclear operations as well as the emergency response to a major nuclear incident.

Following the TMI accident, President Carter transferred the federal lead role in off-site radiological emergency planning and preparedness activities from NRC to FEMA, although on-site activities continue to be the responsibility of NRC. An Executive Order was issued in 1980 that directed FEMA to develop a "national contingency plan" that coordinated the federal agencies' responsibilities, actions and authorities for responding to a nuclear emergency. Under the order, FEMA issued new regulations in 1982 that initiated mechanisms for coordinated planning among federal agencies and among federal, state and local emergency response organizations. EPA was specifically tasked with developing training programs for state and local officials on PAGs and radiation dose assessment, and DOE was tasked with establishing emergency radiation detection and measurement systems and developing a Federal Radiological Monitoring and Assessment Plan (FRMAC, 2007).

A.2.5.5 *Lessons Learned*. Due to the absence of off-site contamination, many of the lessons learned (NRC, 1979) focused on the plant design and operational aspects. Some of these lessons are:

- absence of a well-coordinated communication strategy and timely dissemination of accurate information leads to general mistrust by members of the public;
- lack of trust in the authorities after an incident can hinder further developments in the nuclear industry;
- lack of guidance and radiological criteria complicates response to nuclear incidents; and
- lack of coordinated support exists among federal, state and local agencies.

A.2.6 *Aircraft Accident Involving Thermonuclear Weapons, Near Palomares, Spain (1966)*

A.2.6.1 *Description of the Incident*. On January 17, 1966, a B-52G bomber of the U.S. Air Force Strategic Air Command collided with a KC-135 tanker during mid-air refueling over the Mediterranean Sea off the coast of Spain (DOD, 1975). The B-52G began its mission from Seymour Johnson Air Force Base, North Carolina, carrying four thermonuclear weapons (*i.e.*, hydrogen bombs). Both aircraft were destroyed, and only four out of the 11 crew members survived.

Three weapons landed near the small Spanish fishing village of Palomares, and the other fell into the Mediterranean Sea. Among the three that landed, two had detonation of their high-explosive components and burned, causing the release and dispersion of ^{239}Pu/^{240}Pu particulates from the damaged weapons. The remaining weapon that landed and the one that fell into the sea were recovered without damage. The cleanup effort commenced in late January 1966, involving mostly active duty U.S. Air Force personnel.

The incident led to the termination of U.S. flights carrying nuclear weapons over Spain. Effort and costs toward cleanup were negotiated and agreed to by the Spanish and U.S. governments, with radioactively contaminated soils and waste shipped to United States for burial. Follow-on cleanup efforts were conducted intermittently when contamination was revealed later and an investigation was conducted jointly by Spain's research agency CIEMAT (Energy, Environment and Technology Research Center), and DOE. The Spain and United States agreed to share the cleanup costs of such efforts.

A.2.6.2 *Summary of Impacts*. The release of ^{239}Pu/^{240}Pu particulates from the two destroyed weapons caused various degrees of contamination over an impacted area of 2.26 km^2, which comprised both farmland and noncultivated terrain. The Spanish and U.S. Air Force nuclear specialists cooperated in the initial survey and cleanup of the affected area, performed under the following criteria (Eisenbud and Gesell, 1997):

- soil contaminated above 1.2 MBq m^{-2} was removed, packaged and transported to the United States for burial at the Savannah River Plant (soil in an area of ~220 m^2 was removed and shipped in a total of 6,000 250 L drums);
- arable land below the level of 1.2 MBq m^{-2} was mixed by plowing and harrowing to a depth of 30 cm (an area of ~0.17 km^2 underwent this particular treatment); and
- on rocky hillsides where plowing was not practicable and the contamination level was >0.12 MBq m^{-2}, the soil was removed using hand tools and shipped to the United States.

Contaminated bushes and trees were removed or power-washed. Contaminated roofs and walls were likewise power-washed. Where decontamination was deemed infeasible, the materials of interest were removed. Approximately 1,000 m^3 of soil was removed and shipped in about 5,000 metallic drums for disposal at the Savannah River Plant (Eisenbud and Gesell, 1997).

Follow-on cleanup activities continued over time. For example, some significant contamination was found in 2004. In 2006, the Spanish and U.S. governments developed an agreement to decontaminate the remaining areas and share the workload. In 2008, trenches with previously-stored contaminated earth were found. By the agreement, the U.S. government paid for the decontamination and removal of the waste.

A.2.6.3 *Summary of Long-Term Recovery.* The Spanish government initiated a long-term surveillance program following the environmental remediation operation. This program included bioassay monitoring of plutonium and americium in the affected population. Monitoring of the environment included sampling and analysis of soil, water, vegetation, crops and livestock products, as well as seawater and sediments. Study of the plutonium content in soil and its uptake in vegetation has continued since 1968; the main crops in the region consist of alfalfa, barley and tomatoes (Eisenbud and Gesell, 1997).

Over the decades, the Palomares area has experienced considerable growth that led to the intensive and extensive use of the land, as well development of tourism. The changes in land use compelled the Spanish government to re-establish guidelines to accommodate such developments, specifically regarding the contamination levels within the top 15 cm of soil. Thus, for residual effective doses <1 mSv y^{-1} the use of land is unrestricted. Partial restriction is applied when the assessed residual effective doses are ~ 1 mSv y^{-1} and complete interdiction is imposed for effective doses >5 mSv y^{-1}.

A recent research effort to characterize the remaining contamination has yielded considerable data, including 255,000 records of topsoil data on ^{241}Am in the most contaminated area; statistical measurements by gamma-ray spectrometry have been performed at 581 points with 1,698 samples taken; and 310 boreholes have been created in various locations to evaluate the subsurface migration of the residual contamination. Such information will be important for further evaluation towards final rehabilitation of the contaminated area in the future.

Throughout the course of the incident and the cleanup actions, affected stakeholders (*i.e.*, individual citizens, environmental groups, local media) were closely involved, and fluid communications were maintained. This fluidity has led to a successful effort in the long-term recovery of the affected region.

A.2.6.4 *Special Aspects of the Incident.* The incident was a major international nuclear incident during the Cold War era, and led to changes in military operations regarding transport of nuclear weapons through international airspace. Moreover, the incident resulted in a wide-area (~2 km^2) contamination by plutonium and americium radioisotopes in one specific region of Spain that subsequently experienced expanded residential and commercial land use. The diplomatic efforts have continued, and it appears that agreement is about to be reached between the two governments regarding the final cleanup of the residual contamination in the region, following half a century of negotiations (Minder, 2011).

A.2.6.5 *Lessons Learned*

- cleanup criteria can be adapted and evolve over time to accommodate changing land-use situations;
- stakeholder engagement throughout the cleanup process is important to the recovery of a contaminated area;
- such an international incident requires extensive diplomacy and close collaboration between the involved nations to achieve the long-term cleanup objective;
- cleanup of contamination by plutonium and other actinides requires special knowledge and techniques that have developed over time; and
- long-term monitoring remains as an important measure to ensure protection of health and the environment.

A.2.7 *Windscale Fire (1957)*

A.2.7.1 *Description of the Incident*. Windscale was the site of a plutonium production factory that was constructed on the coast of Cumbria in northwest England in the early 1950s. Two nuclear reactors, known as the Windscale Piles, were each fueled by 180 tons of uranium metal fabricated into more than 70,000 aluminum-clad elements, positioned in 3,440 horizontal channels within nearly 2,000 tons of graphite moderator. The reactor core was cooled by blowing a large volume of air through the channels and out of a 120 m high chimney. In contrast to power reactors, the heat generated by nuclear fission in the Piles was purely incidental to the creation of plutonium for military use. The reactors also were used to generate other radionuclides through neutron irradiation of appropriate target materials placed in channels within the core.

The Windscale Piles posed problems to their operators throughout their service. An unexpected operational challenge was the production of Wigner energy stored in the graphite moderator, which could, if released in an uncontrolled manner, lead to localized high temperatures and the possibility of a fire. Once the process was understood, controlled releases of Wigner energy were conducted in regular annealing procedures. It appeared that it was an uncontrolled localized release of Wigner energy during the ninth annealing of Pile No. 1 which resulted in fuel damage. The metallic uranium fuel and the graphite then reacted with air and started burning. This condition both produced a fire in the core on October 10 to 11, 1957 and the subsequent release of radioactive material from the Pile chimney. The Windscale accident was retrospectively rated as an INES Level 5 incident.

A.2.7.1.1 *Incident scenario*. The first indication of an abnormal condition was provided by air samplers ~1 km away. Activity levels were 10 times those normally found in air, and sampling closer to the reactor building confirmed that radionuclide releases were occurring. Inspection of the core indicated the fuel elements in about 150 channels were overheated. After several hours of trying different methods to extinguish the fire, the reactor core was flooded with water and the plant was cooled down.

The accident caused the release of radioactive material that spread across the United Kingdom and Europe. Several attempts have been made to quantitate the releases of radionuclides and their radiological consequences. However, because the limited instrumentation of the reactor provided little relevant information, the radionuclide discharges were deduced from environmental evidence. The most recent evaluation of atmospheric emissions from the Windscale accident has been published by Garland and Wakeford (2007). Their study has shown that ^{131}I, ^{137}Cs, and ^{210}Po dominated the radiological emissions, and there is sufficient environmental evidence for releases of these radionuclides to allow such releases to be estimated to within a factor of about two. Within 90 % confidence limits, the quantity of ^{131}I emitted (with 90 % confidence) was 900 to 3,700 TBq; ^{137}Cs, 90 to 350 TBq; and ^{210}Po, 14 to 110 TBq.

A.2.7.1.2 *Radioactive contamination*. In the days following the fire, numerous samples of grass, milk, and other agricultural produce were collected from large areas of the United Kingdom and analyzed for radionuclides. Many of the results were mapped to show the pattern of deposition across northern England. The deposition indicated two plumes of activity of similar magnitude. Activity from the first peak was transported initially in an east-north easterly direction, while that from the second peak traveled to the south-southeast. Ground deposition was dominated by ^{131}I, with deposits >4 kBq m^{-2} extending ~75 km east-north east and 140 km south-southeast of the site, covering an area of ~12,000 km^2 (Chamberlain, 1959). The directions of travel for the plumes from Windscale, and the reporting of the accident in the media, resulted in the detection of the plumes at many sites in mainland Europe and even Scandinavia.

A.2.7.1.3 *Affected populations and areas.* The areas affected by deposition from the Windscale fire consisted of mainly rural communities where dairy farming was a common enterprise. Evacuation was not judged to be necessary and monitoring in the first few days after the release indicated that transfer of ^{131}I to foodstuffs, especially milk, was the main hazard. At that time, there was no established guidance for the limitation of radiation dose to members of the public after an accident. Hasty but effective consultations and calculations led to the conclusion that distribution of milk at concentrations in excess of 3,700 Bq L^{-1} should be prevented, in order to limit the absorbed dose to children's thyroids to 200 mGy. Distribution of milk from an area of 207 km^2 was banned from October 12, 1957; following more extensive surveys the ban was extended to 518 km^2 on October 14, 1957. As concentrations of ^{131}I diminished, and as further measurements showed that concentrations of ^{90}Sr and ^{137}Cs were not of concern, restrictions were lifted progressively, and the last area was cleared of restrictions on November 23, 1957.

A.2.7.2 *Summary of Impacts.* The first reports of the radionuclides released during the accident were published in 1958 through 1959. It was clear from these reports that the primary radiological hazard arose from ^{131}I. However, owing to the sensitive nature of the activities being conducted at Windscale, the release of ^{210}Po received much less attention, although a subsequent evaluation of the radiological consequences of the accident (Crick and Linsley, 1984) has shown that inhalation and ingestion of ^{210}Po would have added significantly to the doses incurred. Even so, the maximum individual effective doses were of the order of 7 to 9 mSv and would have been several times greater had a ban on milk distribution and consumption not been implemented (Jones, 2008).

A.2.7.2.1 *Quantitative impacts.* The prompt imposition of a ban on milk supplies had the effect of reducing intakes of ^{131}I *via* the pasture-cow-milk pathway. The average equivalent doses to the thyroid of the local population were typically 5 to 20 mSv for adults and 10 to 60 mSv for children (Clarke, 1989). Because the release was from a tall stack, the peak doses were received 3 km downwind of Windscale. The maximum measured activity in a child's thyroid was reported to correspond to 160 mSv equivalent dose which, when allowance is made for other nuclides and pathways, gives a maximum individual effective dose of ~9 mSv. The contribution to individual effective dose from ^{210}Po is ~2 mSv, of which 90 % is due to inhalation from the plume and 10 % from ingestion of contaminated foodstuffs.

A.2.7.2.2 *Health effects*. The highest organ irradiation was to the thyroid and the expected health effects would be an increase in the risk of thyroid cancer, the majority being nonfatal although requiring treatment (Clarke, 1989). The appearance of any cancers would be over a few decades after irradiation. Clarke (1989), using updated cancer risk coefficients, estimated that the accident had caused or would cause, approximately 100 fatal cancers (of which less than 10 are thyroid cancers due to ^{131}I and about 70, mainly lung cancers, are due to the exposure to ^{210}Po) and approximately 90 nonfatal cancers (of which about 55 are thyroid cancers due to exposure to ^{131}I and about 10 are due to exposure to ^{210}Po).

A.2.7.2.3 *Cleanup costs*. Cleanup costs included: remediation of the Windscale site, organization of the milk distribution ban and disposal of contaminated milk, and compensation payments to farmers. The cleanup of the Windscale site started in 1957 and has been estimated to cost tens of millions of dollars. Dairy farmers received approximately $80,000 for the milk that had to be destroyed in the 44 d for which milk was restricted. Compensation to farmers was limited to only that milk affected by the radionuclide releases.

A.2.7.2.4 *Psychological effects*. Very little has been written about the psychological effects of the accident. In 1957 there was no public debate whatsoever about (the risks of) nuclear technology. However, the way in which the milk distribution ban was implemented would no doubt have caused anxiety in the local community. The general manager of the Windscale site enlisted support from the local constabulary as well as the Milk Marketing Board to waken the farming community during the night of October 12, 1957 to warn them against milking their herds and then distributing their milk through the local area. Local meetings were not held until October 16, 1957, by which time some 600 farms had been affected. The people affected by the milk ban felt as if they were “regarded almost like lepers by their colleagues outside the affected area” (Batten, 2011). The news of the milk ban apparently created more anxiety among members of the public than the fire itself. The unrelenting press reports stigmatized the U.K. nuclear venture and had deep ramifications for the reputation of the agricultural and fishing industries that surrounded the Windscale plant.

A.2.7.3 *Summary of Long-Term Recovery*

A.2.7.3.1 *Late-phase recovery issues*. The milk ban commenced on October 12, 1957 and for most farmers lasted until October 29, 1957. However, for some farmers on the coast near Windscale, the milk ban lasted until November 23, 1957 (*i.e.*, for some 44 d). At that time, there were no contingency plans for managing off-site contamination on the local farmland, and options that would have been implemented today were not considered. Nisbet *et al*. (2009) revisited the Windscale scenario and proposed a strategy for producing milk with activity concentrations of ^{131}I less than today's intervention levels (500 Bq L^{-1}) which would have included the provision of housing and clean feed to dairy livestock. Nisbet *et al*. (2009) also suggested a strategy for disposal of contaminated milk, which would have included storage in slurry pits and subsequent land spreading on the farm at an appropriate time. In 1957, contaminated milk was diluted with water and disposed of down drains.

A.2.7.3.2 *Cleanup criteria*. At the time of the accident there was no recommended level above which intake of ^{131}I would be restricted. Windscale health physicists came to the conclusion that the distribution of milk at concentrations in excess of 3,700 Bq L^{-1} should be prevented, in order to limit the dose to children's thyroids to 200 mSv equivalent dose.

A.2.7.3.3 *Approach to environmental remediation and technology.* Remediation was only required in milk production systems. In 1957, there were few, if any, contingency plans for accidental releases of radionuclides. All that could be done was the imposition of a milk ban and subsequent disposal of the contaminated milk.

A.2.7.3.4 *Waste management and disposal*. Some 3×10^6 L of milk that were collected from cows grazing in an area of >500 km^2 around the Windscale plant were diluted with water and poured down drains and into rivers and the sea. Local reports were of the waterways giving off a sour stench for weeks afterwards. Strict environmental legislation in recent years would not permit such an activity without a site-specific assessment and appropriate consents from the U.K. Environmental Agency.

A.2.7.3.5 *Stakeholder involvement*. Two local meetings were held on October 16, 1957, with a meeting for farmers on October 24, 1957. Subsequent meetings were held with the National Farmers Union on October 25, 1957 to discuss compensation payments to farmers. However, the accident had been shrouded in secrecy, suspicion and rumors. An inquiry into the Windscale accident was instituted by the U.K. government within days of the accident and its report was submitted on October 26, a remarkably short time after the accident. The Prime Minister, whose government was in delicate negotiations to re-establish nuclear weapons cooperation with the United States, decided that only a summary should be published and the full report was only made public 30 y later.

A.2.7.4 *Special Aspects of the Incident*. Jones (2008) had several reflections on the Windscale accident. First, it had wide-reaching effects on the organization of the nuclear industry in the United Kingdom, particularly in respect to safety. The accident ultimately led to the establishment of the National Radiological Protection Board in 1970 and the formation of the Nuclear Installations Inspectorate. Also, the experience of individuals in responding to the accident contributed enormously to the development of radiation protection criteria for nuclear accidents both within the United Kingdom and in ICRP. Jones (2008) was positive about those involved in the response having independently to invent approaches for dealing with damaged and badly contaminated facilities, for rapidly surveying large areas of the environment, for introducing countermeasures to protect members of the public, and for studying the subsequent behavior of deposited radionuclides. They achieved this successfully in a very short time, working under extreme pressure.

Wakeford (2007) considers that the extensive environmental monitoring that took place during and after the Windscale fire provided the evidence on which the authorities decided that a milk distribution ban should be enforced in the west Cumbrian coastal strip. Iodine-131 had been quickly identified as the major radiological hazard arising from the accident. Although health physicists had little guidance available as to what constituted an acceptable limit for the level of ^{131}I in milk, they derived, essentially from first principles, such a limit to constrain thyroid doses, particularly to infants and young children. A milk ban based on these *ad hoc* calculations was a courageous and wise decision, and which limited individual thyroid doses.

A.2.7.5 *Lessons Learned*

- An extensive environmental monitoring program provided the evidence on which to base restrictions on milk. This enabled doses to the thyroid from ^{131}I to be significantly reduced.
- The importance of engaging with the local people in the immediate aftermath of the accident was recognized and led to making arrangements for compensation to farmers whose milk had been restricted.

- There was recognition that the United Kingdom was unprepared for nuclear accidents and afterwards this deficiency was rectified by the establishment of two independent organizations that are still in existence today (albeit they are integrated into larger bodies).

A.2.8 *Marshall Islands (1946 to 1958)*

A.2.8.1 *Description of the Testing*. Eniwetok and Bikini Atolls in the northern Marshall Islands were used as bases for a series of nuclear weapons tests conducted by the United States from 1946 through 1958. Twenty-three nuclear devices were detonated at Bikini Atoll with a combined fission yield of 42.2 MT (UNSCEAR, 2000). An additional 43 atmospheric nuclear tests were conducted at Eniwetok Atoll.

A.2.8.1.1 *Incident scenario*. The Castle Bravo detonation in March 1954 had an estimated explosive yield of 15 MT and deposited widespread radioactive fallout on the islands of Rongelap Atoll about ~160 km east of Bikini, and at a lower level on the islands of Utirik further to the east.

A.2.8.1.2 *Radioactive contamination*. In the immediate aftermath of the detonation, significant quantities of ^{131}I were released. Residual levels of fallout on the atoll have been well characterized and today, the main radionuclides of radiological concern include ^{137}Cs and ^{90}Sr and, to a lesser extent, plutonium isotopes and ^{241}Am.

One key factor that helps explain why ^{137}Cs plays such an important role in contributing to radiation exposure in the Marshall Islands is that coral soils are known to contain little or no clay material and very low concentrations of naturally-occurring potassium. These conditions resulted in an increased uptake of ^{137}Cs from soil and incorporation into plants relative to the rate of ^{137}Cs uptake from typical clay containing soils. Conversely, ^{90}Sr uptake to food products is low because of strong competition from high levels of chemically similar calcium. Plutonium and americium radioisotopes are largely "trapped" in lagoon sediments, with uptake into fish and other forms of seafood extremely low.

A.2.8.1.3 *Affected populations and areas*. Prior to the first nuclear test in 1946, the 167 Bikinians were evacuated to neighboring islands; however some of them returned in the late 1960s and early 1970s but subsequent measurement revealed that their ^{137}Cs body contents had increased by a factor of 10 since their return. In 1978, the population was relocated again and has not returned.

A.2.8.2 *Summary of Impacts*

A.2.8.2.1 *Health effects*. About 50 h after the Castle Bravo detonation, the U.S. Navy removed 64 residents from Rongelap Island. A further 159 residents were later removed from Utirik Atoll. The Rongelap Island exposed group received external radiation doses of ~1.9 Sv effective dose and thyroid doses from ingestion of radioiodines of between 50 Sv equivalent dose for a 1 y old child to ~12 Sv equivalent dose for an adult (McEwan, 2004). Doses to Utirik residents were about one-tenth of those to residents on Rongelap Island, and Utirik residents returned within a few months. Rongelap Islanders did not return to Rongelap until 1957. From 1975 through 1994, an extensive monitoring program was carried out and the data used to develop predictive dose assessments of exposure to hypothetical resident populations to residual fallout contamination in marine and terrestrial environments. The most significant pathway of human exposure to residual contamination in the Marshall Islands was ingestion of ^{137}Cs contained in locally grown crops such as coconut and breadfruit. It is considered that without remedial action or restrictions on their behavior, those returning to Bikini Atoll would on average receive an annual effective dose of 4 mSv from the remaining contamination. The highest plausible dose to people who might consume only locally grown foods rather than the more typical mix of local and imported foods is estimated to be ~15 mSv y^{-1} effective dose (ICRP, 2009).

The U.S. Atomic Energy Commission (now the U.S. Nuclear Regulatory Commission) appointed a medical follow-up program for the exposed groups. The principal finding was damage to the thyroid gland with increased incidence of thyroid nodules. The later appearance of thyroid effects and one case of acute leukemia were of concern to the Rongelap people who therefore abandoned Rongelap again in 1985.

A.2.8.2.2 *Cleanup costs*. There is no information specifically available on cleanup costs. However, under a Compact of Free Association, a sum of $150 million was granted to the Marshall Islands as compensation to Marshallese who had suffered any personal injury, or loss of/damage to property as a result of the testing program. The grant came into force in 1986.

A.2.8.2.3 *Psychological effects*. Jones (2004) suggests that the psychological effects on the affected populations have occurred because of the life changes that were imposed on them through no fault of their own. A lack of control over the incidents that resulted in radioactive contamination of their surroundings created an increased level of frustration, which manifested itself in a lack of trust in the whole system.

A.2.8.3 *Summary of Long-Term Recovery*

A.2.8.3.1 *Late-phase recovery issues*. The importance of the ingestion pathway for ^{137}Cs (which contributes 90 % of the effective dose) in the years following the atmospheric tests has focused late-phase recovery issues on reducing the transfer of ^{137}Cs to food products.

A.2.8.3.2 *Cleanup criteria*. The Republic of the Marshall Islands has adopted a cleanup standard of 0.15 mSv y^{-1} effective dose above background.

A.2.8.3.3 *Approach to environmental remediation and technology.* On the basis of extensive trials, it has been estimated that a program of potassium treatment, repeated every 4 or 5 y, would reduce the concentration of ^{137}Cs in typical Bikini foods to well below the Codex Alimentarius Commission guidelines for international trade in foodstuffs (Codex, 2012). Projected doses would be reduced to ~0.4 mSv y^{-1} effective dose from the normal mix of local and imported foods and 1.2 mSv y^{-1} effective dose from a diet of exclusively local produce (ICRP, 2009). There is also the advantage that the addition of potassium increases the growth rate and productivity of some food crops. An alternative option would be to remove the topsoil from crop-growing areas as well as the residential areas. While this would be effective in reducing exposures, it would generate very large volumes of soil requiring disposal. Furthermore, replacement topsoil would have to be imported. An optimal solution may be to use potassium on the agricultural areas and remove topsoil in the residential areas.

A.2.8.3.4 *Stakeholder involvement and communication*. DOE has implemented a series of strategic initiatives to address long-term radiological surveillance needs in the Marshall Islands. The plan is to engage local atoll communities in developing shared responsibilities for implementing radiation surveillance monitoring programs for resettled and resettling populations in the northern Marshall Islands. Using the pooled resources of DOE and local atoll governments, individual radiological surveillance programs have been developed in whole-body counting and plutonium urinalysis. These programs are used to accurately track and assess doses delivered to Marshall Islanders from exposure to residual fallout contamination in the local environment. The program has also supported scuba diving and other commercial operations to enhance the economic base of affected communities. One tool that has been useful in the U.S. long-term management of the situation in the Marshall Islands is providing the necessary financial and technical support for the affected population to establish their own independent technical group to advise them and to look out for their best interest.

A.2.8.4 *Lessons Learned*

- Lack of information about the contamination and evidence of related health effects resulted in a lack of trust in the authorities that lasted for many years.
- Strategic initiatives to engage local communities in environmental surveillance monitoring as well as health surveillance programs are improving trust.
- The presence of long-lasting environmental contamination has enabled research to be carried out and strategies developed for reducing exposures from residential areas and locally grown foodstuffs.

A.2.9 *Liberty RadEx, a Recent Exercise in the United States Against Radiological Terrorism (2010)*

A.2.9.1 *Background*. Liberty RadEx (LRE) was the first National Tier II (involving federal strategy and policy focus with significant simulation), full-scale exercise in the United States that focused on "post-emergency" (30 to 90 d after the attack) response and recovery planning. It was the largest drill (the incident lasted for 5 d) of its kind, sponsored by EPA to test the country's capability to cleanup and help communities recover from a dirty-bomb terrorist attack. The incident was co-sponsored by the Pennsylvania Department of Environmental Protection Bureau of Radiation Protection and the City of Philadelphia Office of Emergency Management. Over 700 individuals participated in LRE representing 35 federal, state and local government agencies; nine community groups; 14 private businesses; two universities; and six foreign countries (EPA, 2011b). Prior to the exercise, participants were given basic radiation awareness and other necessary training.

A.2.9.2 *Incident Scenario*. The exercise was held in the City of Philadelphia, Pennsylvania during the week of April 26, 2010. The incident follows the "National Planning Scenario 11, Radiological Attack – Radiological Dispersal Device" (EPA, 2010; 2011a). The scenario used was based on a terrorist attack using an RDD which assumes a suicide bomber loaded a van with ammonium nitrate mixed with diesel fuel and 85.1 TBq of ^{137}Cs (in powder form) and detonated the explosives in the center city during the day. All emergency responses were assumed to ensue in accordance with their requisite protocols. The radioactive fallout was assumed to be carried by the prevailing wind and deposited up to ~80 km northward over residential, commercial, industrial, suburban and rural areas, impacting roadways, hospitals, schools and businesses.

A.2.9.3 *Objective*. The purpose of LRE was to test federal, state and local post-emergency response to an RDD incident in an urban environmental setting pursuant to ESF #10 (Oil and Hazardous Materials), the Nuclear and Radiological Incident Annex, and the interface with other key ESFs and response agencies. The focus was on post-emergency response, assessment and cleanup of an RDD, and community recovery.

A.2.9.4 *Scope*. LRE included five distinct exercise activities addressing various aspects of the scenario. These activities included the following:

- *Full-scale activities as specified by the ESF #10*: The activities include the following incident command/unified command functions:
    - response planning including health, environment and radiological impacts assessment; waste and cleanup planning; and operational period planning;
    - field assessment, mitigation and cleanup;
    - public information and community outreach; and
    - coordination with EPA offices, other agencies, and the FEMA Joint Field Office.
- *Community recovery facilitated discussion activities*: The community recovery facilitated discussion centered on ESF #6 (Mass Care, Emergency Assistance, Housing, and Human Services) and ESF #14 (Long-Term Community Recovery). The activities involved participants from various agencies, organizations, and ESFs normally supporting sheltering/housing and community recovery. The issues related to the Community Advisory Panel were also discussed.
- *Water Team tabletop activities*: The Water Team tabletop activities comprised two separate activities; one at the Philadelphia Water District's Baxter Drinking Water Plant, and the other at the Northeast Water Pollution Control Plant. These activities focused on both the "emergency" phase (*i.e.*, immediately following the incident) support to water facility managers for development of short-term actions, and long-term remediation plans. The latter includes sampling throughout the treatment system, solid collection, residual

and filter media evaluations/removal, and proper disposal of radioactive contaminated materials.

- Other activities included tactical response and evidence recovery activities for the law enforcement units (not related to long-term recovery), and also the general issues associated with community recovery.

A.2.9.5 *Summary of the Exercise*. As the first full-scale exercise directed toward late-phase recovery from an RDD incident in the City of Philadelphia, LRE was a considerable success.

Overall, the success included a fairly large participation from agencies and interested sectors and the addressing of key issues including: deployment and logistics, response support, completion of targeted initiatives, exercise of safety measures, exercise of the Community Advisory Forum (the Community Advisory Panel and the Technical Advisory Panel), radioactive waste disposal, exercise on the venues and field activities, and all drills and training sessions. In essence, the exercise demonstrated success in achieving the EPA approach to its mission in addressing its national response responsibilities as well as its ESF #10 and related activities. The exercise however did not specifically address the development of cleanup criteria or issues associated with the optimization process.

A.2.9.6 *Special Aspects of the Incident*. The exercise was coordinated by EPA with participation from many other agencies and interested parties including citizens' groups. It also included nine venues in an attempt to illustrate the different cleanup issues (*i.e.*, subway station, central city, waste treatment facilities, and historical park). The exercise illustrated the value of the activities involved but also identified a number of issues that will need further efforts to be addressed in the future.

A.2.9.7 *Lessons Learned*

- The exercise accomplished a daunting effort in coordination among the many agencies and responsible groups in achieving the late-phase cleanup objective. This coordination can only be accomplished by a concerted, full-scale exercise such as LRE.
- While the exercise was largely successful and accomplished many of its objectives, the sheer magnitude of its scale cast some doubt regarding follow-on exercises to LRE in light of budget constraints. Thus, other alternatives including the development of modular tabletop exercises with focused scope would be beneficial to the nation's preparedness efforts on late-phase issues.

- There was a conspicuous lack of attempt to include the optimization process in the exercise, thus leading to considerable ambiguity in the determination of the cleanup criteria and the related issues such as cleanup priorities or land-use scenarios in the contaminated zones.
- Although radioactive waste issues were included in the exercise, more in-depth effort needs to include estimating the magnitude of waste generated, feasibility of temporary waste staging areas, and developing practical infrastructure to accommodate the large amount of waste generated. The lack of the "real-incident" atmosphere and preparation of the stakeholders (such as potential future land-use options) prevented a realistic involvement of stakeholders in crucial cleanup decisions.

A.3 Lessons from Nonradiological Incidents

There are many examples from around the world of nonradiological incidents that have a long-term recovery component (*e.g.*, natural disasters, chemical spills, acts of terrorism). The case studies described here are restricted to incidents that have occurred in the United States; one caused by a natural disaster (Hurricane Katrina) and two caused by acts of terrorism (*e.g.*, anthrax mailings and September 11, 2001):

A.3.1 *Hurricane Katrina Disaster (2005)*

A.3.1.1 *Description of the Incident*. Hurricane Katrina of 2005 was among the deadliest and most destructive hurricanes, and was certainly the costliest one in U.S. history.

The hurricane was first formed as "Tropical Depression Twelve" over the southeastern Bahamas on August 23, 2005. It was then upgraded to a tropical storm on August 24 when it was assigned its name Katrina. It continued to move toward Florida and made landfall on the morning of August 25 as a Category 1 hurricane before entering the Gulf of Mexico. The storm continued to intensify on August 27 to Category 3, and eventually grew to Category 5 on the morning of August 28, with a maximum sustained wind of 280 km h^{-1}. On the morning of August 29, Katrina made its second landfall near Buras-Triumph, Louisiana. By this time, it had decreased to a Category 4 hurricane with winds near 205 km h^{-1}. It then proceeded through southeastern Louisiana and made a third landfall and maintained its strength into Mississippi. It was finally downgraded to a tropical depression when it reached Tennessee.

On August 26, Governor Kathleen Blanco declared a state of emergency in Louisiana, which was followed by Governor Haley

Barbour of the State of Mississippi on August 27, when the federal emergency was also declared and FEMA was given full authority for the response. Fearing the massive failure of the levees, Mayor Nagin of the City of New Orleans issued the first-ever mandatory evacuation of the city on the morning of August 28. Both voluntary and mandatory evacuations were also issued for large areas of southeast Louisiana and coastal Mississippi and Alabama, involving a population of about 1.2 million residents. By late morning on August 29, some large portions of the New Orleans levees failed, and the disaster ensued.

A.3.1.2 *Summary of Impacts*

A.3.1.2.1 *Economic impacts*. Hurricane Katrina was one of the worst natural disasters ever suffered by the United States. The uninsured damages topped $100 billion (Bloomberg News, 2005) and the insured losses were originally estimated at $34.4 billion (Powell, 2005). The total estimated costs of $108 billion by the National Oceanic and Atmospheric Administration (Blake and Gibney, 2011) also has Katrina at the top among the documented hurricanes in history. New Orleans was hit hard by the storm which flooded roughly 80 % of the city, destroying over 182,000 homes (Liu and Plyer, 2010).

A.3.1.2.2 *Environmental impacts*. Katrina also created profound impacts on the environment, among them the substantial erosion of the beach by storm surge and the complete devastation of the coastal areas. It was estimated by the U.S. Geological Survey (USGS, 2006) that 560 km^2 of the land was transformed to water as a result of the combined effects of Hurricanes Katrina and Rita (September 2005). The lands lost were prime breeding grounds for marine mammals, seabirds, and migratory species. The damage forced the closure of 16 national wildlife refuges. The storm also caused oil spills from 44 facilities throughout southeastern Louisiana, with some oil entering the ecosystem.

A.3.1.2.3 *Health impacts*. The confirmed death toll due to direct and indirect deaths totaled 1,836 people, mainly from Louisiana (1,577) and Mississippi (238), while 135 people remain missing in Louisiana. The federal disaster declaration covered ~233,000 km^2. About three million people were left without electricity. In the City of New Orleans, an estimated 90 % (or about 1,400,000) evacuated the city, 5 % (or about 80,000) sheltered in the Louisiana Superdome, and another 5 % remained in the city.

A.3.1.3 *Summary of Long-Term Recovery.* Planning for the recovery from the hurricane and the rebuilding of New Orleans began on September 30, 2005. On that day the Mayor formed the Bring New Orleans Back Commission, which was intended to "oversee the development of a rebuilding plan for the city" (Liu and Plyer, 2010). By November 2005, the Commission issued its first report, which "recommended that all officials establish one united request to Congress for support." While the Bring New Orleans Back Commission continued its work, the New Orleans City Council began its own planning process. In July 2006 the New Orleans City Planning Commission hired advisors to develop the Unified New Orleans Plan, which was meant to incorporate all of the prior plans. Thus, it took over 22 months after Katrina for the city to approve a recovery plan. However, some businesses reopened in the French Quarter and Bourbon Street in less than three months, and in <1 y the Superdome was reopened to host a professional sports event. All these actions happened despite the city needing many more years to achieve a full recovery.

Even with the recession and the Deepwater Horizon oil spill of April 2010, the New Orleans metro area has begun to recover, as evidenced by the fact that as of 2010, >90 % of the population has returned and 85 % of the jobs are filled relative to pre-Katrina levels. The area is seeing growth in knowledge-based industries (versus the traditional industries including tourism, fishing and petrochemicals), and average wages have increased by nearly 14 %. The poverty rate is the lowest it has been since 1979, although it is still high at 23 %. The quality of local schools has improved as has local healthcare and the criminal justice system.

There are still some remaining challenges. The local economy is still reliant on a few industries, and the proportion of college-educated workers in the metro area is lower than the national average. Housing costs continue to burden renters, with 58 % of city renters and 45 % of suburban renters spending >35 % of their pre-tax income on housing. This situation is worse than the national average, which indicates that out of all renters, 41 % pay >35 % of their pre-tax housing income on housing.

The lack of a comprehensive plan clearly slowed the process of rebuilding, and cost the area both in dollars and in the millions of volunteer hours from residents who became involved in the process. Having several planning processes going on simultaneously consumed time and effort that could have been better spent. One lesson that can be learned is the importance of cities preparing before an incident occurs and making sure that the citizens are supportive of the plan. Although the process is believed to have increased the area's resilience, it seems that the process could have provided the same benefits prior to the disaster.

Another lesson to be learned revolves around the role that risk plays in decision making. If individuals believe that an area is susceptible to disasters, this will make it less likely that they will be willing to locate there or to invest in businesses there. It is important that the plans convince people that the area will be safe (or at least safer) in the future.

It is also important to realize that wealthier areas will be better able to recover using private dollars from insurance and other sources. Poorer areas will require more funds from the government or from philanthropists (Baade *et al.*, 2005). Monies are also needed to shore up social institutions such as schools so that individuals will return to the area.

Finally, the importance of developing resilience is obvious. As discussed by the Brookings Institute (Liu and Plyer, 2010), the keys to doing this are a strong and diverse regional economy, large proportions of skilled and educated workers, wealth, strong social capital, and community competence. Working on improving these items prior to an incident will clearly help speed the recovery process.

A.3.1.4 *Special Aspects of the Incident*. The disaster caused by Hurricane Katrina constitutes a major natural incident in recent U.S. history. The magnitude of the hurricane (at one time reaching Category 5, the most severe level) and its lingering, unpredictable nature, coupled with the breakdown in all levels of government, produced an unprecedented catastrophe leading to a massive evacuation of the affected regions. This calamity and its accompanying casualties and extensive destruction of the communities has taken many years to resolve. The incident also led to a dramatic change in the federal government's response to a major disaster. The subsequent availability of resources and the community's adaptability have led to progresses being made toward a full recovery from the disaster in the region.

A.3.1.5 *Lessons Learned*

- Lack of a well-coordinated effort by all levels of government led to initial indecision regarding evacuation of the populations.
- Recovery is often initiated by local communities, such as businesses (in the case of New Orleans, the French Quarter and Bourbon Street was open for business within three months of the incident). Such initiatives can be accelerated by government resources and assistance.

- Lack of a comprehensive recovery plan led to a slow rebuilding process. Therefore it is important for cities to prepare before an incident to enhance resiliency, and help ensure future success.
- Building a resilient society requires a carefully designed recovery plan which is fully supported by stakeholders. Government should ensure the availability of sufficient resources and support in case of a major disaster.

A.3.2 *Anthrax Attacks in the United States (2001)*

A.3.2.1 *Description of the Incident*. There was a series of anthrax attacks shortly following the September 11, 2001 terrorist attacks in the United States. The anthrax attacks came in two waves. The first set of attacks consisted of anthrax letters mailed to the several news media in New York and Boca Raton, Florida. The letters were postmarked at Trenton, New Jersey and dated September 18, 2001. Several people were reported being infected. The second set of attacks consisted of two letters, bearing the same Trenton postmark and which were mailed on October 9. Letters were also addressed to the U.S. Senate: one to Tom Daschle, the Senate Majority Leader, and the other to Patrick Leahy, Chairman of the Senate Judiciary Committee. The discovery of the letter to Daschle's office prompted a major evacuation of several government offices, including the Hart Senate Office Building where Daschle's sixth floor suite was located. People who worked in and around the area of the office were also tested for anthrax exposure, of whom 25 tested positive. All those infected were subsequently treated with antibiotics, as were all the congressional staff workers.

While the letters sent to the media contained a course brown material containing anthrax, the letters sent to the two U.S. senators contained a more potent, highly refined dry powder consisting of ~1 g of nearly pure spores.

After an extensive and prolonged investigation by the U.S. Federal Bureau of Investigation, it was finally concluded that the suspect, Bruce E. Ivins, was a government employee who had worked for over 18 y at the U.S. Army Medical Research Institute of Infectious Diseases at Fort Detrick, near Frederick, Maryland, and who subsequently committed suicide during the investigation in 2008. The Federal Bureau of Investigation later announced that Ivins acted alone in committing the crime.

A.3.2.2 *Summary of Impacts*. For the series of attacks combined, at least 22 individuals developed anthrax infections, with 11 of the infected individuals suffering from the especially life-threatening syndrome of inhalation infection. Among them, five died of inhalation anthrax. The attacks created nationwide anxiety and caused fear of further attacks.

Cleanups at the Hart Senate Office Building, several contaminated postal facilities, and other U.S. government and private office buildings demonstrated that decontamination is possible, but it is time consuming and costly. Clearing the Senate Office Building of anthrax spores cost $27 million, according to the U.S. Government Accountability Office (GAO, 2003). Cleaning the Brentwood Postal Facility outside Washington, D.C. cost $130 million and took 26 months. Since the attacks in the autumn of 2001, newer and less costly methods have been developed. The principal means of decontamination is fumigation with chlorine dioxide gas.

EPA was one of the principal federal agencies involved with the cleanup at the Hart Senate Office Building and various other attack sites, and used its authorities and funding under CERCLA to conduct investigations and cleanup, with Congress restoring some of the spent funds ($22 to $23 million) through appropriation. Since the attack affected a branch of the federal government (Congress) outside of the Executive Branch, responsibility for oversight and funding of the Senate cleanup was largely shouldered by the Hill.

The anthrax attacks, in combination with the September 11, 2001 terror attacks, have spurred significant increases in U.S. government funding for biological research and preparedness. In 2004, Congress passed the Project Bioshield Act, which provides $5.6 billion over 10 y for the development and purchase of new vaccines and drugs.

A.3.2.3 *Summary of Long-Term Recovery.* The anthrax attacks were considered to be incidental, and public awareness of incidents tends to fade with time. The incidents did not appear to carry any long-term effect once the cleanup efforts were successfully conducted. Some important observations and lessons learned can be gained from the experience:

- It proved to be very effective for EPA to work through the National Response Team in addressing the anthrax contamination. The National Response Team is closely linked to the National Oil and Hazardous Substances Pollution Contingency Plan.
- The National Response Team chose to establish a scientific advisory group and a community advisory group to advise decision makers and to involve community stakeholders in providing input to the response. Additionally, technical

assistance materials were generated to assist in this and other cleanups.

- Although the circumstances of the anthrax attacks were novel in many ways, experience from past "traditional" cleanups proved valuable to the decontamination. In particular, past cleanup responses involving asbestos were informative and similarities were apparent in establishing appropriate engineering controls and personal protective clothing, with antibiotic prophylaxis or therapy administered to workers and affected personnel.
- A "zero growth" cleanup criterion was established by the two advisory groups and the role of a scientific support coordinator (on-site) was crucial to the credible and necessary building of a strong science foundation for the decontamination activities. Additionally, EPA affirmed that it was particularly helpful to bring in technical consultants from academia and industry to advise in the situation.

A.3.2.4 *Special Aspects of the Incident*. This case was particularly difficult for law enforcement agencies. It took nearly 7 y to conclude the case, which was committed by a lone perpetrator. The anthrax attacks, which occurred soon after the September 11 terror attacks, engendered particular fear among members of the public. It has also caused considerable disruptions of society, among which was the careful screening and scrutiny of all packages handled by the postal system.

A.3.2.5 *Lessons Learned*

- Cleanup effort can be expedited at the national level with both considerable efficiency and concerted attention from the federal government.
- Current statutory cleanup requirements can be invoked to conduct a focused, limited cleanup with success.

A.3.3 *Terrorist Attacks of September 11 at New York City (2011)*

A.3.3.1 *Description of the Incident*. The terrorist attacks of September 11, 2001 were the largest organized and coordinated attacks of their kind in U.S. history. The incidents consisted of a series of four attacks upon the United States that involved the New York and Washington, D.C. areas and Shanksville, Pennsylvania. On the morning of September 11, 2001, 19 terrorists from the Islamic militant group al-Qaeda organized in four separate suicide missions that involved four hijacked passenger jet aircraft. Two of the planes, American Airlines Flight 11 and United Airlines Flight 175, were intentionally crashed into the Twin Towers of the World Trade Center (WTC) in lower Manhattan. Both towers caught fire and collapsed within 2 h. Another plane, American Airlines Flight 77, was later crashed into the Pentagon in Arlington, Virginia. The fourth jet, United Airlines Flight 93, crashed in a field near Shanksville, Pennsylvania. This last hijacking was thwarted by passengers attempting to take control of the flight before it reached the hijackers' intended target of Washington, D.C. The attacks resulted in almost 3,000 human causalities. The casualties involved citizens from more than 90 countries (DOS, 2006).

In response to the WTC attack, the New York City Fire Department immediately deployed 200 units to the site, and was joined by personnel dispatched by the New York Police Department as well as the Port Authority police. Search and rescue efforts ensued. As conditions worsened, an evacuation order was issued by New York Police Department and most of the police personnel were able to evacuate the towers. However, some firefighters did not receive the evacuation order and perished in the building collapses. It took several months of intense effort at the WTC to finally clear the site by the end of May 2002.

The attack at the Pentagon severely damaged the building; the impact and the resulting fires caused one section of the building to collapse.

A.3.3.2 *Summary of Impacts*

A.3.3.2.1 *Health impacts*. In all, there were 2,996 confirmed deaths including 19 terrorists. Among the 2,977 victims, 2,753 were involved in the attack at the WTC in New York (including the passengers of American Flight 11 and United Flight 175); 184 involved in the attack at Pentagon (including passengers of American Flight 77); and 40 involved in the crash at Shanksville, Pennsylvania (all passengers aboard United Flight 93).

Aside from the casualties as a direct result of the attacks, subsequent debilitating health effects and illnesses have been reported among rescue and recovery workers. The burning and collapsing of the Twin Towers and the adjacent buildings created large quantities of toxic debris containing known carcinogens (NYT, 2006). Health effects also extended to residents and office workers, and some deaths have been linked to the toxic dust; some of the effects expressed as impairment of lung function with persistent symptoms. An estimated 18,000 survivors have developed illnesses (Shukman, 2011), and litigations regarding the toxic exposures continue to be filed years after the attacks. Since such effects were not previously recognized by health authorities, more research and studies for toxic materials in such an incident are warranted.

A.3.3.2.2 *Property impacts*. The attack on the WTC destroyed its pair of principle structures known as the Twin Towers and also seriously affected numerous surrounding buildings, including WTC Buildings 3 through 7, St. Nicholas Greek Orthodox Church, and the Marriott Hotel (FEMA, 2002). Other buildings including the World Financial Center also suffered varying degrees of damage. Some buildings were deemed uninhabitable due to the toxic conditions, and others were condemned due to the extended damage. Other buildings that were only slightly damaged were subsequently restored.

The Pentagon in Arlington, Virginia was severely damaged. One section on the west side of the building collapsed as a result of the impact and resulting fire.

A.3.3.2.3 *Economic impacts*. The September 11 attacks caused considerable short-term economic impacts to the affected regions, particularly New York. The negative reaction from the financial sector caused an estimated loss in U.S. stocks of $1.4 trillion in valuation within the first week after the attacks (Fernandez, 2001). The total estimated insurance loss was nearly $40 billion (Belasco, 2011; Makinen, 2002), one of the largest in U.S. history. In New York, the incidents resulted in a loss of 430,000 job-months and $2.8 billion of wages in three months. The airlines and aviation industry also suffered tremendous losses in business due to the mandatory grounding of flights in response to the incidents and the effect was compounded by public fear of air travel. Also seriously affected was tourism in general, and specifically in New York where tourism is an important industry generating about $25 billion per year. Perhaps the most important long-term detriment to the economy is the substantial commitment to upgrading the overall security of the nation for both private and public sectors. The September 11 attacks also led to the U.S. wars in Iraq and Afghanistan, collectively referred to as the "War on Terror," which has so far (2013) cost the nation an estimated several trillion dollars.

A.3.3.2.4 *Societal impacts*. The terror attacks have had a profound impact on society, such as substantially instilling a strong sense of patriotism among members of the public. Perhaps the most important impact is the shaping of the government's policy toward terrorism. Domestically, measures have been taken to strengthen the defense against terrorism, including establishing anti-terrorism laws. The U.S. Department of Homeland Security (DHS) was established in the United States as a direct response to terrorism.

A.3.3.3 *Summary of Long-Term Recovery.* The reconstruction at WTC took an extended period. While other damaged buildings were restored, including the WTC PATH (Port Authority) Rail System Station (opened in 2003), the rebuilding of the original WTC site was delayed. The centerpiece of the reconstruction is a building known as "One World Trade Center." With a planned height of 541 m, One WTC will become the tallest building in North America. Other buildings near the site are to follow once the One WTC building is completed.

The damaged section at the Pentagon was rebuilt and occupied 1 y after the attacks. At the Shanksville, Pennsylvania site, in the midst of grove of trees, a national memorial has been built.

Overall, the recovery efforts in the affected areas appear to be working smoothly after a decade following the incidents. They do not appear to have created long-term recovery issues.

A.3.3.4 *Special Aspects of the Incident*. The September 11 incident signifies the first major coordinated terrorist attacks (on three separate sites simultaneously) on U.S. soil. The incident led to a fundamental overhaul of the U.S. homeland defense and its associated organizational changes. Following the attacks, DHS was created by the Homeland Security Act of 2002, which consolidated 22 agencies (including FEMA) into one single federal agency. DHS has a threefold mission: to prevent terrorist attacks in the United States, to reduce America's vulnerability to terrorism, and to minimize the danger from potential attacks and natural disasters.

A.3.3.5 *Lessons Learned*

- As in many other incidents, communication remains a primary issue involving rescue workers as well as members of the public. More effective communication mechanisms are very much needed for responding to future incidents.
- For a major metropolitan area such as Manhattan, there is a need to build in resilience (such as high-performance buildings) into the existing infrastructure against potential attacks (DHS, 2010b).
- Long-term health effects should be considered for incidents involving toxic materials.
- Establishment of the World Trade Center Health Registry (NYC, 2002) for monitoring the health effects in rescue and recovery workers, residents, children, city employees, and others is a model for other types of incidents.

A.4 Summary of Lessons Learned from Historic Incidents

Based on the wealth of information gained from past incidents, as described here in the various case studies, valuable lessons have been identified for issues involving long-term recovery from a major incident.

A.4.1 *Conclusions on Lessons Learned*

As radiological incidents are extremely rare, preparedness for them often requires extensive knowledge and concerted effort to plan response and mitigation of the potential unpredictable consequences and will require a highly region-specific approach. Furthermore, an incident that triggers a major disaster could itself be protracted over an extended period of time, rendering the response and recovery difficult and slow.

By studying a selection of past incidents of both radiological and nonradiological origins, it has been possible to identify some clear lessons to be considered when developing recovery plans; these are discussed below.

Based on the information obtained, long-term recovery issues encountered in a major nuclear facility incident or a terrorist attack using an RDD or IND would not be significantly different from those associated with past nuclear or radiological incidents with a similar scale of impacts. The long-term issues will largely remain with the widespread contamination that would be caused by the incident, although specific issues will be both incident and site specific.

A.4.2 *Resilience*

Recovery is best achieved where communities are resilient, yet resilience has to be built in advance in conjunction with the stakeholders (lessons from Hurricane Katrina). To accomplish a timely recovery, sufficient incentives are required; the primary “drivers” toward recovery include political, economic and cultural factors, with each factor contributing to a collective desire of the community to return to a normal life. The economic factor, in particular, is important in all cases since it governs every aspect of recovery (*i.e.*, remediation, removing and disposal of the debris; decontaminating the land; managing the contaminated waste; rebuilding the communities; re-establishing the commerce; resuming public services), all of which require viable economic initiatives. Such activities have been fully illustrated by past incidents that have seriously disrupted society. For example, businesses reopened in the French Quarter and Bourbon Street in New Orleans in less than three months following Hurricane Katrina of August 2005, and in <1 y, in September 2006, the Superdome hosted its first professional sports event (*i.e.*, a New Orleans Saints football game) since Katrina. All these activities were happening despite the city eventually taking many more years to achieve a full recovery. It is therefore critical for businesses, communities and government to work closely together to define priorities and effectively use available resources toward a timely recovery.

A.4.3 *Communication*

One of the most common and also most challenging aspects associated with incident response and recovery is effective communication. Effective communication requires accurate information that can be widely disseminated in a timely manner in order to both enhance the response effort and mitigate potential impacts, including stigma. The stigma suffered by the affected populations has been widely reported following a major nuclear or radiological incident (IAEA, 1988; 2006a; TEPCO, 2011). This stigma has resulted in situations ranging from denied freedom of travel, to access to services, and to loss of tourism and businesses. The long-term stigma can linger long after the incident. It is thus important to address such issues in the pre-incident planning stage to enable an effective public communication and education effort toward the long-term recovery. The Litvinenko incident showed good practice in communications as evidenced by the excellent communication links between government departments and agencies, stakeholders and members of the public. In contrast, other incidents such as TMI, Goiânia, Chernobyl, and the Marshall Islands were shrouded in secrecy and had long-lasting impacts on trust in the authorities and stigmatization of the affected population and area.

A.4.4 *Stakeholder Engagement*

Large accidents such as those witnessed at Chernobyl and Fukushima have shown that recovery from a severe incident is not likely to return the affected communities to full normalcy. Rather, a "new normal" would be created under which stakeholders may find it acceptable to continue to live their lives. Thus, the important issues including choice of decontamination methods, cleanup criteria, waste disposal sites and future land use will require extensive interactions with stakeholders to reach a consensus. There have been many examples of where stakeholder engagement has been used successfully over the years, although sometimes the success (*e.g.*, Chernobyl, Palomares, and Marshall Islands) happened as a result of the failure of other nonparticipatory approaches that were used first. More recently, the involvement of stakeholders at national, regional and local levels has been the preferred method for developing acceptable recovery strategies (*e.g.*, Fukushima, Litvinenko).

Involving stakeholders in the process of responding to and recovering from a radiological incident is central to the "whole-community" approach. To this end, the pre-incident planning effort ought to reach out to identify various levels and groups of stakeholders who would be consulted on major decisions and consolidated into the process through a series of collaborative proceedings.

Pre-existing arrangements in the United Kingdom for recovery worked well for the Litvinenko incident, particularly because they were regularly exercised with stakeholders for multiple risk scenarios. When engaging with stakeholders it is important to recognize the diversity of the affected society in such sectors as culture, race, social status, economy, and religion. In addition, there may be a multitude of stakeholder groups involved in various decision-making processes, some of which may contain inherent conflicts of their own. For example, in an attempt to expedite the cleanup effort in an affected municipal area, some nearby radioactive waste staging areas would need to be identified and designated, and perhaps an ultimate disposal site not too far from the city would need to be developed in a plan. In such a case, potentially conflicting interests may develop among the different groups of stakeholders representing the municipal area, the temporary staging areas, and the ultimate disposal area (*e.g.*, LRE). This potential issue, of course, also affects the populations living adjacent to the transportation corridors where shipment of waste may be quite frequent. Thus, all such issues need to be identified by the pre-incident planning effort and be frequently exercised and coordinated to resolve the potential conflicts or issues. The continued effort in reaching out and engaging relevant stakeholders is therefore essential for reaching acceptable decisions for long-term recovery.

One important aspect of the whole-community approach to a major disaster is to properly integrate the communities into the recovery planning process. Consequently, the recovery effort needs to be driven and initiated primarily by the stakeholders' specific needs at the local and regional level, and be coordinated and assisted by the authorities at all the appropriate levels. For this reason, there should not be a top-down, imposed approach toward long-term recovery, as acceptance by stakeholders remains a premise for the success of the efforts. The involvement of local communities in the recovery program has proven to be successful in many different situations, regardless of the source of the contamination (*e.g.*, Fukushima, Marshall Islands, and Palomares).

A.4.5 *Research and Development*

Society in general is quite unfamiliar with the issues associated with rare incidents, particularly those that could cause widespread contamination. This reality exists despite extensive experience and knowledge in the cleanup of contaminated environments, mostly associated with industrial activities. For example, most of the cleanup activities performed in the United States to date generally fall under the existing statutory provisions (NCRP, 2004) that are prescribed for specific regulatory conditions, but not necessarily for response to large-area incidents such as caused by large accidents or terrorist acts involving RDDs or INDs.

Incident-specific situations generally require specific state-of-the-art technology in order to expedite the cleanup process. The technologies developed by the nuclear industry may become obsolete or inappropriate when it comes to addressing specific contamination situations. For example, the extensive contamination of soils that followed both the Chernobyl nuclear reactor and Fukushima nuclear accidents cannot be addressed by the routine excavation and removal methods that are commonly used in the decommissioning activities of nuclear facilities. Continuing research and development has been a key part of improving the effectiveness of cleanup technologies in Palomares and the Marshall Islands. Similarly, the Chernobyl nuclear reactor accident has spawned numerous research and development programs in many affected countries over the years, and as a result new methods for managing contamination of the food chain have been validated. Some of this research has been transferable to the situation in Fukushima and new methods for decontamination of the environment are being researched.

A.4.6 *Pre-incident Recovery Planning*

Pre-incident recovery planning includes a number of issues that cannot be properly accommodated by routine policy and standards. In general, special provisions and considerations will be required, and these will take time to be developed and agreed upon, likely impeding recovery efforts. These issues may include: decontamination and technology; waste generation, storage, treatment and disposal; waste packaging and transportation; land-use options; contamination of environmental media including soil, air and water; stakeholder involvement and interactions, education and training for possible self-help programs; and alternative economic plans. Issues such as radioactive waste clearance, temporary waste staging and storage, and soil decontamination technology have become acute problems in recent nuclear or radiological incidents including the Fukushima Dai-ichi nuclear accident (IAEA/NEFW, 2011). But, however, all of the radiological case studies considered in this Report had serious waste handling and disposal issues (*e.g.*, Chernobyl, Fukushima, Goiânia, Litvinenko and Palomares). Waste management seems to be a universal challenge and one for which many lessons have already been identified. Thus, it is recommended that appropriate policy and waste acceptance standards be developed specifically to address waste issues for the recovery planning process.

A.4.7 *Long-Term Monitoring of the Environment and Public Health*

Long-term management of the residual contamination and radiation exposure should include monitoring of the health effects in the affected populations; monitoring environmental contamination (such as reconcentration or recontamination of radionuclides due to weathering effects or human activities); and monitoring of residual contamination in foodstuffs, infrastructures, properties, drinking water and commodities. Monitoring provides reassurance and confidence to those living and working in the contaminated areas that the situation is being well-managed and that health and well-being of the population is of paramount importance. Although it took time to establish, environmental monitoring and health surveillance have proved to be essential components to various national recovery programs following the Chernobyl nuclear reactor accident. It was also key to the recent success of the recovery program in the Marshall Islands. Throughout the process, proper communication about the monitoring strategy needs to be maintained with stakeholders until a consensus decision is reached to discontinue the monitoring. To this end, it is important to formulate a cleanup policy with long-term monitoring and management in mind. As an example, the WTC Health Registry is the largest registry to track the health effects of a disaster in American history.

A.4.8 *Significance of Ongoing Lessons Learned from the Fukushima Dai-ichi Nuclear Accident*

One of the most important lessons learned pertains to the ongoing effort to bring recovery to the regions in Japan where the unprecedented natural disaster in the form of the Great East Japan earthquake and subsequent tsunami caused the Fukushima Dai-ichi nuclear accident of 2011. The Fukushima accident serves as a living case for recovery from a major nuclear incident that caused widespread contamination and affected a large population. While the Fukushima Dai-ichi NPP continues toward being stabilized, the recovery effort has only now begun in earnest in Japan. The effort led by the Japanese government and private sectors is making headway, and extensive international collaborations are taking place. The initial findings and lessons learned (IAEA/NEFW, 2011) indicate a strong need to formulate appropriate policies, develop technologies, enhance public communications, bolster stakeholder interactions, and expedite the cleanup efforts. It is important to continue such collaborations in an attempt to broaden the access to the best approach and technology toward long-term recovery. Such lessons learned will serve as extremely valuable input not only to the current recovery effort in Japan, but will also help to establish an excellent knowledge base for future planning efforts.

Appendix B

Current Practice in Managing Radioactive Waste

B.1 Introduction

Effective and efficient recovery from an RDD or IND attack or a major reactor accident will require a cogent, well-prepared waste management strategy that fully details:

- approach to waste characterization and volume estimation;
- establishment of temporary waste storage criteria and treatment strategies;
- considerations for final disposal site(s) selection; and
- waste packaging and transport requirements.

However, there are a number of challenges within the nation's current LLRW management scheme that warrant further consideration by the appropriate levels of government to deal with a large-scale, wide-area contamination incident. Both NA/NRC (2006) and NCRP (2002a; 2002b) have strongly recommended improving the current approach to radioactive waste management by moving to a more risk-based or risk-informed system.

B.2 Waste Classification and Inherent Deficiencies

Waste that contains radioactive materials is generally considered to be radioactive waste (NRC, 2013a). However, waste is generally managed not by what it is, but by how it was produced. In the case of a radiological terrorist attack or major nuclear accident, various levels of contamination will be generated by initial blast forces and subsequent deposition from a radioactive plume. In the case of an IND, radionuclides may also result from neutron activation of materials in soil, buildings, or other structures near the detonation. Although it is probable that most waste could generally be characterized as LLRW [probably for the most part the Class A Waste Type (the lowest designation)], there does not exist any systematic method for specifically characterizing waste by type, class or activity. Additionally, an important feature of the waste classification system for nuclear fuel-cycle waste in the United States is that there is no definition of what LLRW is, only a definition of what it is not. This is referred to as a definition by exclusion. An unfortunate result of this approach is that the LLRW category can range from innocuous waste to relatively hazardous waste that remain hazardous over long periods of time. Since the definitions of the different classes of fuel-cycle waste are based on the origin of the waste, rather than on risk-based considerations, waste in different classes can pose similar risks and require similar disposal approaches, or waste within the same class can have widely divergent risks (NCRP, 2002a).

In the United States, no cutoff level exists below which the waste can no longer be considered radioactive. A general class of exempt waste has not been established in law or regulations; in fact, NRC is currently prohibited by law from establishing such a class (NCRP, 2002a). Class A designates the lowest hazard waste[9] (Table B.1 displays waste types for key radionuclides) and there is no level less than Class A which might indicate no need for regulatory controls for the purpose of radiation protection. This lack of a cutoff level is a difficult issue since it is likely that a considerable portion of the waste from a radiological terrorist attack or major reactor accident will contain very low concentrations of radionuclides, even near background levels. This situation is known as having a lack of "clearance level."

Following the Fukushima Dai-ichi accident, IAEA urged Japanese authorities that "It is important to avoid classifying as 'radioactive waste' waste materials that do not cause exposures that would warrant special radiation protection measures. The [IAEA] Team encourages the relevant authorities to revisit the issue of establishing realistic and credible limits (clearance levels) regarding associated exposures. Residues that satisfy clearance level can be recycled and reused in various ways, such as construction of structures, banks and roads" (IAEA, 2011a).

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[9] "Lowest hazard" in this context refers to long-term intrusion scenarios and does not weigh the potentially more significant immediate hazard from shorter-lived radionuclides of concern. This shorter-term immediate hazard could be a factor in managing waste if being handled by workers who are not trained in radiation protection (*i.e.*, workers who would be considered members of the public).

TABLE B.1—*Classification of LLRW for near-surface disposal by radionuclide concentration (adapted from NRC, 2013b).*

Radionuclides	Maximum Concentration in GBq m^{-3}		
	Class A	Class B	Class C
^{137}Cs	3.70×10^1	1.63×10^3	1.70×10^5
^{90}Sr	1.48×10^0	5.55×10^3	2.59×10^5
^{60}Co	2.59×10^4	—[a]	—[a]
Radionuclides with half-life <5 y (total)[b]	2.59×10^5	—[a]	—[a]
^3H	1.48×10^3	—[a]	—[a]
^{63}Ni	1.29×10^2	2.59×10^3	2.59×10^4
^{63}Ni in activated metal	1.29×10^2	2.59×10^4	2.59×10^4

[a] No limits established for Class B or C, but practical considerations such as the effects of external radiation or heat generation on transportation, handling and disposal may limit concentrations.

[b] For short-lived radionuclides: if radioactive waste does not contain any of the radionuclides listed in Table 1 of NRC (2013b) (long-lived radionuclides chart), classification is determined by values reflected in Table 2 of NRC (2013b) (reflected above). However, if radioactive waste does not contain any nuclides listed in either of these two tables, it is Class A.

An important benefit of establishing a clearance level would be a reduction in resources required for waste treatment and disposal (NCRP, 2002a). Note that response officials and associated governments could establish both a clearance level for material that is to be disposed of in landfills and a separate clearance level for "beneficial use" such as use in construction materials or road materials. Additionally, another clearance level could be set for "free-release," or use without any restrictions. These are known as "conditional" and "unconditional" clearance levels. The potentially massive waste volume expected from an RDD, IND, or reactor accident would greatly highlight the shortcomings of the U.S. radioactive waste classification system, and in particular the restriction of having no lower boundary to Class A and no clearance level.

Additionally, it is important to note that there is uncertainty about how the current regulatory definition of LLRW by NRC (2013a) might apply to a terrorist situation. The current definition of LLRW is a definition by exclusion (*i.e.*, not spent nuclear fuel and not high-level radioactive waste) and the circumstances of the terror incident and the radioactive materials involved would likely be outside the statutory/regulatory scheme set forth for AEA processes and activities (Section 4.2.2.2.3).

NCRP Report No. 139 (NCRP, 2002a), *Risk-Based Classification of Radioactive and Hazardous Chemical Wastes*, enumerated a number of important deficiencies in the current system:

- The radioactive waste classification system is complex, and it is not transparent to members of the public, who are increasingly involved in decisions about management and disposal of waste (and who would certainly be involved as part of an optimization process), and it is not understandable by anyone but a studied expert.
- The classification system lacks a set of principles for determining when a quantity of waste contains sufficiently small amounts of radionuclides that it can be exempted from regulatory control as radioactive material. The lack of a general class of exempt waste increases in importance as the resources required for management and disposal of radioactive waste increases (a critical consideration magnified by a catastrophic nuclear or radiological incident) compared with the resources required for management and disposal of these materials as nonradioactive waste, and it may preclude possible beneficial uses of slightly-contaminated materials.
- The classification system for fuel-cycle waste is increasingly unable to accommodate in a logical and defensible manner

newer forms of waste that were not envisioned when the classification system was first developed.

- The classification system for fuel-cycle waste is essentially qualitative. As a result, there is substantial ambiguity about classification. This ambiguity has led to needless disputes about classification of specific waste that are largely unrelated to important issues of protecting human health.
- The definition of LLRW is particularly problematic. Contrary to the common meaning of "low-level" and the meaning of this term when this waste class was first defined, LLRW can contain high concentrations of shorter- and longer-lived radionuclides similar to those in high-level radioactive waste, as well as relatively low concentrations of any radionuclide. Thus, the definition of LLRW is not related to its radiological properties or to requirements for safe management and disposal. The definition only by exclusion also may foster mistrust by members of the public because the simple question of what LLRW is cannot be given a direct answer.

In contrast to the U.S. system, the IAEA recommended classification system includes a general class of exempt waste. Exempt waste is defined in terms of an individual dose to a member of the public resulting from waste disposal that is considered negligible. Specifically in the IAEA system, concentrations of radionuclides at or below levels corresponding to annual effective doses to members of the public from waste disposal of 10 µSv effective dose, have no radiological restrictions (NCRP, 2002a). Establishment of a level for exempting waste (or setting a clearance level) during post-incident recovery activities is an important consideration for decision makers to weigh, within appropriate legal and policy constraints.

B.3 Estimating Volumes of Radiological Waste and Understanding Remaining Disposal Capacities

As options are considered regarding cleanup goals and the target risk (*i.e.*, dose) and concentration determined, waste volumes will vary accordingly with the largest volumes of waste generated for the lowest-level goals or most constraining values. Additionally, more waste may be created through the treatment process. Clearly development and application of waste estimation tools will be useful for emergency planners for planning purposes as well as during actual responses.

In large-scale scenarios, such as INDs or massive nuclear reactor accidents such as Fukushima Dai-ichi, estimated waste volume may be in the tens of thousands, and perhaps even millions of cubic meters. By comparison, records show that during routine operations total Class A waste disposals average slightly >64,000 $m^3\ y^{-1}$ and Classes B and C waste average slightly <900 $m^3\ y^{-1}$ (NA/NRC, 2006). Consequently finding permanent disposal solutions will be difficult with the projected large volumes from a catastrophic incident. Disposal capacity at commercial LLRW disposal facilities would be severely strained or even insufficient. Response planners or government officials could find it difficult (even in nonemergency situations) to get comprehensive, accurate, and up-to-date figures on remaining capacity at the nation's LLRW sites, hazardous waste disposal sites, and municipal landfills, since that information is often protected as "proprietary." Decision makers and planners may find it useful to become familiar with the *Waste Business Journal*, which periodically publishes a *Directory of Waste Processing and Disposal Sites* that contains information on over 8,300 waste-processing facilities (WBJ, 2013).

B.4 Waste Treatment and Staging

Various forms of waste treatment will be required for the waste volume resulting from a large-scale radiological/nuclear incident. These incidents will generate large volumes of contaminated building materials, soils, asphalt, and concrete; trees, shrubs, and other organic material; and decontamination residues. Treatment strategies will have to be closely coordinated with overall waste management strategies.

Treatment can make waste more suitable for disposal (*e.g.*, stabilization in concrete); remove contaminants (*e.g.*, surface cleaning or filtration); and reduce volumes through evaporation, grinding, crushing and shredding. Technologies to reduce volume at the site of the incident may help reduce demands on available disposal capacity. Similarly, suitability of a waste stream for a given disposal option may hinge on its manner of treatment or packaging. On the other hand, care should be taken not to unwittingly select a treatment method that would concentrate radionuclides beyond levels acceptable at given facilities. Additionally, there may be a need for treatment of hazardous constituents to meet the Resource Conservation and Recovery Act (RCRA, 1976) land disposal restrictions, if the decision is made to conduct disposal using these sites.

Lessons learned from past incidents and exercises have revealed that radioactive waste management is critical and in particular, waste staging areas (*i.e.*, those used for temporary storage of waste) need to be identified and properly designed. The staging areas should be near the location of the incident, but should be suitable for storing the waste throughout the entire cleanup effort if necessary. Protection measures and criteria will need to be identified and specified in the planning process. Depending on waste characterization and several other factors, options for final waste disposal will range from disposal at local landfills to transport to licensed disposal facilities across the nation. Selection of such options as the latter will have profound impacts on cleanup feasibility, schedule and costs.

B.5 Final Disposal Sites

Both commercial and government options for permanent disposal of radioactive waste are limited and may not provide the capacity for final disposal of all waste from a major nuclear or radiological incident. Table B.2 provides a listing of commercial LLRW facilities' lifetime capacities or their annual rates of waste acceptance. Because much of the waste may have minimal radioactive contamination, waste facilities regulated under RCRA, specifically RCRA Subtitle C and Subtitle D landfills, could be used. However, site-specific determinations to use a particular landfill will need to be rigorously evaluated, with those using Subtitle D landfills even more so than those using Subtitle C landfills. EPA has examined many of the issues associated with using Subtitle C landfills for disposal of "low-activity" radioactive waste under a more routine, risk-based framework (EPA, 2003). Brief definitions of these landfill categories from the EPA website are provided below (EPA, 2013a):

> "RCRA Subtitle C landfills are those landfills which are authorized under RCRA to accept hazardous waste for disposal. RCRA is the comprehensive federal law that, among other things, regulates the management of certain highly dangerous wastes from the moment they are generated until their ultimate destruction or disposal. Landfills authorized to accept these wastes must follow very stringent guidelines for their design and operation."

RCRA Subtitle D regulates the management of nonhazardous solid waste. It establishes minimum federal technical standards and guidelines for state solid-waste plans to promote environmentally sound management of solid waste. Subtitle D regulates:

- garbage also known as municipal solid waste (*e.g.*, milk cartons and coffee grounds);
- refuse (*e.g.*, metal scrap, wall board, and empty containers);
- sludges from waste treatment plants, water supply treatment plants, or pollution control facilities (*e.g.*, scrubber slags);

TABLE B.2—*Commercial LLRW disposal facilities.*[a]

Disposal Facility	Waste Allowed	Various States Access	Capacity
Energy Solutions, Barnwell, South Carolina	Class A, B, C	Atlantic Compact (Connecticut, New Jersey, South Carolina)	425 $m^3\ y^{-1}$
Energy Solutions, Clive, Utah	Class A, and mixed LLRW	Open to all states	$1.16 \times 10^6\ m^3$ with plans to more than double capacity
U.S. Ecology, Richland, Washington	Class A, B, C	Northwest and Rocky Mountain Compacts (11 states)	$0.71 \times 10^6\ m^3$
Waste Control Specialists, Andrews, Texas, near the New Mexico border[b]	Class A, B, C, and mixed LLRW	Texas Compact (Vermont, Texas; Texas Compact Commission considering providing access to out-of-compact states)[b]	$0.065 \times 10^6\ m^3$ for commercial use and $0.74 \times 10^6\ m^3$ for federal (DOE) use

[a] Data taken from the following corporate websites: Energy Solutions (ECP, 2014), US Ecology (2014), and Waste Control Specialists (WCS, 2014).

[b] Waste Control Specialists intends to construct and operate a separate federal (DOE) disposal capacity in conjunction with its commercial facility.

- nonhazardous industrial waste (*e.g.*, manufacturing process wastewater and nonwastewater sludges and solids); and
- other discarded materials, including solid, semisolid, liquid, or contained gaseous materials resulting from industrial and commercial activities, (*e.g.*, mining waste, oil and gas waste, construction and demolition debris, medical waste, agricultural waste, household hazardous waste, and conditionally-exempt small-quantity generator waste).

Using a broad range of disposal facilities may expedite the disposal of radiological waste, reduce the expenditure of resources, and more quickly reduce risks to public health and the environment by reducing the need for longer-term interim storage and enhancing the more rapid clearing of temporary storage sites. Following a major nuclear or radiological incident, the decision of whether to dispose of radioactive waste in RCRA facilities, should not be taken lightly and considered only after extensive discussions with appropriate regulators, other stakeholders, and the affected communities; after a thorough deliberation on all the options; and after a technically sound assessment that human health is adequately protected.

Conjoining the AEA framework and RCRA framework is not easy. While there are some important similarities, there are also some significant differences. As NCRP Report No. 139 (NCRP, 2002a) points out, the approach to regulating radionuclides under AEA is essentially opposite to the risk management paradigm for hazardous chemicals under several environmental laws, including RCRA. This difference in approach is largely driven by what is deemed "acceptable" and "unacceptable" risk and how each framework defines its goals (NCRP, 2002a). For landfills in particular, the AEA approach requires performance objectives which limit releases to off-site populations, as well as future protection of inadvertent intruders. RCRA does not require off-site impact modeling, and the post-closure period may be limited to 30 y and be under private ownership. For some citizens, these differences may lead to lower confidence in the ability of non-LLRW sites to contain radioactive materials, and require further evaluation. However, the need to maintain the flexibility to streamline the response operation and expedite the recovery process has been reflected in lessons learned from major incidents.

However, if use of RCRA landfills is deemed suitable and acceptable, important cost, time, and even health benefits may be gained in disposal of the massive waste volumes produced by large-scale, wide-area contamination incident. A recent NA/NRC (2006) study noted that there are far more RCRA Subtitle C permitted facilities

(20) than LLRW commercial facilities (four) in the United States and that some Subtitle C facilities currently accept NRC-exempted LLRW on a case-by-case basis, and many Subtitle C landfills regularly accept technologically-enhanced naturally-occurring radioactive material waste within permit conditions. The NRC exemption process (NRC, 2014b) can be slow and expensive as demonstrated by the very low number of industry applications for this exemption (only 10 over a 10 y period). The NA/NRC report also noted that there are a few instances where Subtitle D municipal landfills have accepted or will accept very small concentrations of radioactive waste. For example, the state of Texas (TAC, 2011) has "…determined that municipal landfills (Subtitle D) offer sufficient protection for certain types of radioactive material… with very short half-lives, and have defined in their state regulations the kinds and amounts of radioactive waste that may be so disposed" (NA/NRC, 2006). While disposal of radioactive waste in RCRA landfills can be very controversial, prudent decision makers need to understand the nation's entire range of waste management infrastructure to evaluate options judiciously and to present and understand ideas in stakeholder and community discussions in a transparent and scientifically informed process.

B.6 Low-Level Radioactive Waste Disposal Facilities

If RCRA-based disposal of waste from a major nuclear or radiological incident with wide-area contamination is deemed not feasible or unacceptable, commercial LLRW disposal facilities may be the only suitable option, perhaps in combination with assistance from DOE to the affected state(s) or the construction of new, specifically designed landfills in the affected region. Existing LLRW landfills are limited in number and capacity as shown in Table B.2.

LLRW disposal is controlled in part through regional compacts as described in the Low-Level Radioactive Waste Policy Act of 1985 (LLRWPAA, 1985), as amended in 1988. Through the compact system states have authority to join together with other states to provide capacity for LLRW disposal but also can choose to deny waste from outside the compact. Rules and procedures have been developed by each compact and may vary from compact to compact.

Given a significant terrorist attack or national emergency, there may be more willingness by some LLRW compacts to provide disposal to out-of-compact waste, perhaps with the agreement that the affected state(s) will internally manage a substantial share of the total waste. Additionally, NRC has emergency access authority (NRC, 2014c) to these disposal facilities but it is not certain how this authority may or may not be exercised in a large-scale incident (the NRC emergency access provision has never been invoked as of the date of this Report).

DOE operates federal disposal facilities at a number of its sites but there are legal restrictions on acceptance of non-DOE waste. For an incident of national significance such as an RDD, IND, or major reactor accident (the response to which would likely involve DOE), it may be possible to create Executive Orders, directives, and agreements that would provide access to these disposal areas.

B.7 Waste Transportation and Packaging

Packaging and transporting radioactive waste is a substantial undertaking during the late-phase cleanup process. This will likely entail:

- preparing appropriate waste containers (size and integrity specifications);
- packaging the waste in containers for shipping across municipal streets (in case of an affected urban area);
- designating shipping routes from the incident site or contaminated areas to the local staging areas for storage; and
- decisions regarding transportation by highways, railways or waterways, as appropriate to off-site temporary and/or final disposal sites.

B.8 Need for a Risk-Informed Radioactive Waste Management Approach

As decision makers and emergency preparedness officials plan for responses to large-scale releases and wide-area contamination from radiological or nuclear incidents, it is important to appreciate that if the nation moved toward a more risk-informed and risk-based radioactive waste management system, several of the current challenges facing planners might be eased, and regulatory oversight of these wastes could be simplified. As both NA/NRC and NCRP have previously pointed out, a risk-based approach would be more inherently logical and defensible (NA/NRC, 2006; NCRP, 2002a). Relevant to difficulties of enormous-volume waste management following a nationally-significant incident, the NA/NRC (2006) study begins with the following passage:

> "By far the largest volumes of radioactive wastes in the United States—millions of cubic meters—contain only small concentrations of radioactive material. These low-activity radioactive wastes (LAW) should be regulated and managed according to their intrinsic hazardous properties and, thus,

> the degree of risk they pose for treatment, storage, and disposal. The current regulatory structure is based primarily on the wastes' origins rather than their actual radiological risks. There is no scientific basis for applying different degrees of control to wastes that pose similar risks or applying similar controls to wastes that pose very different risks. Such inconsistencies are inherent in the current system."

It is therefore important that a risk-based radioactive waste management approach, together with a set of waste acceptance criteria, be developed to create a streamlined waste disposition system that could accommodate the huge volumes of waste generated during the late-phase recovery actions. This approach likely provides the only basis capable of addressing the urgent need for managing waste disposal that arises from an RDD or IND terrorist attack or a major NPP accident.

Appendix C

Decontamination Cleanup Technologies for Large Areas

C.1 Introduction

A large-scale nuclear or radiological incident will likely cause widespread contamination affecting urban and rural environments. The extensive experience from previous decommissioning of legacy sites within the nuclear industry or cleanup following large-scale nuclear accidents described in Section 7 provides practical solutions to achieving desired cleanup levels (DOE, 2011; Eckerman *et al.*, 1988; EPA, 1990; 1996; 2006; 2007; IAEA, 1989a; NCRP, 2006; Nisbet *et al.*, 2009). This appendix is designed to help decision makers identify decontamination technologies that are potentially useful for removing radioactive contaminants from buildings, structures, equipment surfaces, soils, and aquatic ecosystems. It provides basic summary information on decontamination technologies and refers the reader to other sources for a more comprehensive assessment of cleanup technologies or management options. When considering these technologies for large-scale environmental cleanup efforts, several criteria should be considered including:

- overall protection of human health and the environment (CERCLA, 1980);
- compliance with applicable or relevant and appropriate requirements;
- long-term effectiveness;
- reduction of toxicity, mobility and volume;
- short-term effectiveness;
- implementation ability;
- cost;
- type of material (*e.g.*, metal, asphalt, concrete, soil, wood);

- type of surface [*e.g.*, rough, porous, nonporous, coated (*e.g.*, paint, plastic)];
- composition of contaminant (*e.g.*, activation or fission products, actinides);
- chemical and physical form and size of contaminant [*e.g.*, solubility, aerosol, flocculent particles, complex compound with other materials (for many decontamination processes, the smaller the particle, the more difficult it is to remove from a surface)];
- decontamination factor required;
- proven efficiency of the process;
- method of deposition (the distribution of the contamination and its adherence to the surface can depend on whether the deposition was wet or dry);
- availability and complexity of the decontamination equipment;
- waste generation and ultimate disposal method;
- need to condition the secondary waste generated;
- occupational doses and doses to members of the public resulting from decontamination;
- other safety, environmental and social issues, especially stakeholder acceptance and involvement into the decision-making process;
- availability of trained staff; and
- amount of work involved and the difficulty in decontaminating the equipment used for the cleanup if it is to be reused.

In the United States, applying decontamination technologies to cleanup is also referred to as "treatment" methods as discussed in the National Oil and Hazardous Substances Pollution Contingency Plan (EPA, 1994). In Part 300.5, treatment is defined by whether the technology can or will alter "…the composition of a hazardous substance or pollutant or contaminant through chemical, biological, or physical means so as to reduce toxicity, mobility, or volume of the contaminated materials being treated." Furthermore, such technology should generally achieve a standard of treatment of 90 to 99 % reduction in concentration or mobility. From an environmental media standpoint, treatment may include stabilization, soil washing, excavation, *in situ* vitrification, and other methods. In a similar manner, treatment of surface contamination includes activities that remove or stabilize the material on the surface. These may include the various washing or abrasive technologies that remove the contaminant from the surface. Treatment may also include stabilization or fixation technology in which an additive chemically or physically bonds with the contaminant and by immobilizing it prevents the contaminant from migrating.

In the case of large-scale decontamination efforts on the order of tens to thousands of square kilometers, the cleanup approach should consider criteria that incorporate a more holistic approach. This may be somewhat contrary to traditional cleanup efforts where:

- sites are easily controlled and characterized against a clean surrounding background;
- cleanup goals are very close to background levels;
- conservative decisions are based on the most likely exposed individuals;
- an expectation that the affected environment will return to pre-incident conditions; and
- existing regulation and government policies are enforced.

Cleanup and recovery of a contaminated area that impacts hundreds of thousands to millions of people should also address nonradiological factors that ultimately may drive decisions to ensure a viable recovery for the affected population (*e.g.*, social and economic factors). While long-term recovery should focus on saving lives by reducing unnecessary risks, the realities of conducting a traditional cleanup based solely on a radiological risk approach should be realized as being nearly impossible because the size and scope of the incident will likely grow beyond the capabilities of the existing national infrastructure and capabilities.

A shift to more practical cleanup levels, population-based protection, unrestricted access, iterative decontamination efforts, sound self-help techniques, community empowerment, and acceptance of a "new normal" will provide flexibility for the decision makers to implement a recovery strategy that is based on the realities of the scenario, in which attempts to decontaminate an area occur while the surrounding area remains contaminated. In summary, as the size and scope of a radiological incident grows from small to large, the recovery solutions go from:

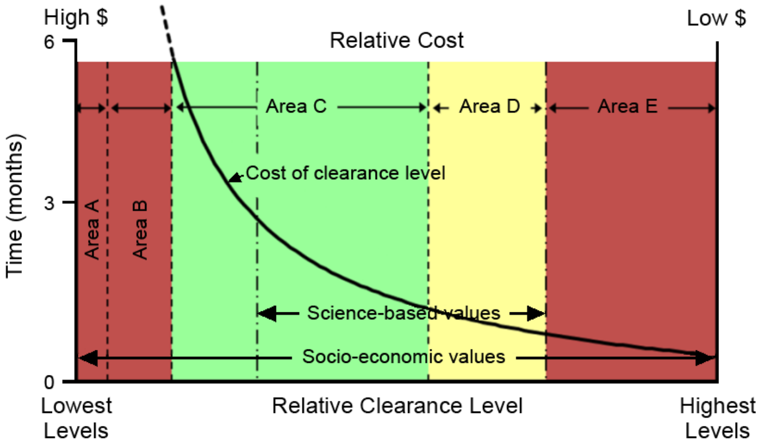
- precautious to practical decision making;
- individual to population protection;
- controlled to uncontrolled access;
- site-specific cleanup goals to an iterative cleanup process;
- return-to-normal expectation to an acceptance of a new normal; and
- an examination of achievable conditions in light of regulations and policies.

Figure C.1 captures the range of issues associated with a large-scale recovery effort. This continuum incorporates the holistic approach to generate compromise and optimize the outcome. The political/social perspectives, which may be influenced by public health and environmental concerns, can be shifted toward center when balanced with the limitations of cost and the "back-to-business" attitude. The latter two concerns should also shift to center based on the need to convince an evacuated population that it is safe to return, and address any reluctance on the part of consumers, both within the community and in adjacent communities (to include consumers in other states and the international market place), that the products are safe.

In summary, the final decontamination process selected will depend on the best overall balance among the factors listed above to maximize the benefit to people and the environment. This appendix describes 39 decontamination technologies or management options that may be implemented in populated areas following a radiological incident. A summary table provides the advantages, limitations, and qualitative rankings for each application to a large-scale environmental cleanup, considering waste, operational and cost issues. A more comprehensive summary of these technologies is available from DOE (2011), EPA (Eckerman *et al.*, 1988; EPA, 1990; 1996; 2006; 2007), IAEA (1989b), and Nisbet *et al.* (2009). Additionally, since a great deal of research on radiocesium in the environment has been published as a result of environmental cleanup efforts worldwide, NCRP published Report No. 154 (NCRP, 2006) that provides:

- a summary of general knowledge on the properties, geographic distribution, and sources of ^{137}Cs in the environment;
- site-specific descriptions of releases, environmental levels, transport pathways, and specific issues relative to ^{137}Cs at three major DOE facilities;
- relatively detailed treatments of the radioecology of ^{137}Cs in terrestrial and aquatic ecosystems, including biogeochemical transport mechanisms and transport modeling concepts; and
- brief summary of the more generic management issues, remediation techniques, and benefit-cost considerations of alternative strategies for lands contaminated with sufficient levels of ^{137}Cs to warrant concerns about public health and environmental quality.

Some remediation techniques detailed in NCRP Report No. 154 are included in this Report.



Area	Cost	Time	Socio-Economic	Scientific & Medical
Area A	Too costly	Years – decades	Unjustified	Unjustified
Area B	Costly	Years	Extreme	Unjustified
Area C	Within acceptable costs	Months – years	Acceptable	Extreme – acceptable
Area D	Within acceptable costs	Months	Acceptable – extreme	Justified
Area E	Least costly	Weeks – months	Extreme	Unjustified

Fig. C.1. Issues associated with a large-scale recovery effort (DOE, 2012).

C.2 Decontamination Technologies or Management Options for Contaminated Surfaces

The following paragraphs briefly describe the decontamination technologies or management options [as referred to in the international community (Nisbet *et al.*, 2009)], for contaminated surfaces that may be considered in a large-scale environmental cleanup effort. Many technologies are effective in different environments (outdoor versus indoor) and on different surfaces (*e.g.*, concrete, steel, brick, wood). The techniques described are organized into the general categories of biological, chemical and physical remediation methods. The specific application of each technology may be inherent in its use (*e.g.*, concrete scabbling) or be applied based on its ability to be implemented in the field (*e.g.*, high-pressure washing of streets). Where possible, a target application is provided in the description of each technology.

C.2.1 *No-Action Alternative*

The development of management plans for contaminated ecosystems with long-lived radionuclides like ^{137}Cs should give careful consideration to the no-action alternative, unless the site is so small and so highly contaminated that aggressive remediation action is clearly necessary. Individuals with specific knowledge of the levels of certain long-lived radionuclides like ^{137}Cs and resulting human health and ecological risks at various sites in the United States and elsewhere have determined that in many cases remedial action may not be warranted. However, it is important to reach such a conclusion for any given site only after a scientifically rigorous risk assessment is performed for an agreed-upon land-use scenario, and stakeholders agree to this course of action (NCRP, 2006). For example, this option could be considered if the monitoring information and assessment tools indicate that the doses to people living in the area are small and the risks are low. Other factors could make the decision to do no cleanup attractive, such as a lack of resources or a very large area being affected (Nisbet *et al.*, 2009).

C.2.2 *Biological Decontamination Technologies*

Biological decontamination uses microorganisms and higher-order plants to alter the distribution or mobility of the contaminant in soils or sediments. Phytoremediation includes both phytoextraction (the concentration of contaminants into harvestable portions of plant biomass) and phytostabilization (the use of plants to minimize off-site losses of contaminants through erosion and leaching). The potential for successful application of phytoextraction and/or phytostabilization techniques to contaminated soils in the United States depends strongly on site-specific conditions. Factors such as cleanup goals, level of radionuclide contamination, depth of contamination, soil properties, the presence of other toxic materials, disposal of harvested biomass and climatic conditions can all influence the likelihood of success. Phytostabilization may already be an important process at some sites where natural vegetation intercepts radionuclides migrating from contaminated sites to surface receiving waters (*e.g.*, Garten, 1999).

C.2.2.1 *Microbiological Effects*. Biological techniques of soil remediation often involve the use of microorganisms to facilitate the breakdown of toxic materials to something less hazardous. The targets of biological remediation are generally organic compounds. Such approaches would not be effective for reducing the activity of radionuclides except possibly to alter their availability or mobility. Tsang *et al*. (1994) showed that some metals become more mobile under the influence of active microorganisms, depending on the properties of the soil and the metal. They also found that cysteine is an effective agent for enhancing the release of some metals from soil. A soil bacterium (*Pseudomonas putida*) has been used to determine its adsorption of cesium and other elements and its influence on the mobility of metals in soils (Ledin *et al.*, 1997). The investigators examined adsorption as a function of pH and ionic strength for low metal concentrations. For example, cesium was shown to exhibit adsorption by the bacteria (a dissociation constant K_d of ~10^2 to 10^3), but adsorption was higher for other metals (*e.g.*, the K_d for mercury adsorption was on the order of 10^6).

C.2.2.2 *Phytoextraction*. Partial removal of radiocesium from soils can be accomplished by relying on the natural uptake of metals by plants, termed phytoextraction. The radioactive vegetation is then collected and disposed of separately as a hazard, thus reducing biologically-available contaminant concentrations in soil. This technique has been applied to radiocesium remediation of contaminated soil (Lee, 2000). Phytoremediation can potentially minimize both ecosystem disturbance and cleanup costs.

More research is needed on maximizing plant removal of radionuclides from soil by genetically modifying plant properties, and increasing radionuclide availability to roots without adversely affecting biomass production or increasing the leaching losses of radionuclides to receiving waters. Implementation of phytoremediation should consider the possible trade-offs between costs, biomass production, increased radionuclide availability, bioaccumulation, time to recovery, and the ultimate disposal of contaminated plants.

Additionally, depending on soil and plant type, phytoextraction of cesium by vegetation can play a role in remediation, but at the same time can bring soil-bound cesium to the surface, thereby increasing the chance for human exposure. Plant uptake factors are dependent on a multitude of environmental parameters and can vary by orders of magnitude across sites and even within a given general location. Attempting to model the behavior of cesium in soils can be quite challenging because of parametric complexity and our lack of knowledge sufficient to completely describe cesium binding in the complex of soil structures in specific soil types. Caution should be used in the application of remediation models because remediation decisions can be highly sensitive to judgments regarding numerical values of uptake factors. The use of site- or area-specific values is imperative for reliable environmental assessments.

C.2.2.3 *Phytostabilization*. Phytostabilization can greatly reduce the migration of radionuclides such as ^{137}Cs that tend to sorb strongly to soils by preventing or at least reducing soil erosion. Studies at Oak Ridge National Laboratory suggest that forest vegetation can be important to the retention of radionuclides at contaminated sites (Garten, 1999). Removal of vegetation reduces evapotranspiration and potentially increases the export of water, nutrients and radionuclides from contaminated sites. Such losses can be critical to environmental protection when water quality in streams draining contaminated areas is approaching standards set to protect the public health. If methods of planting and soil amendments increase the availability of ^{137}Cs for phytoextraction, then phytostabilization buffer zones might be incorporated into field designs to minimize erosional and leaching losses of ^{137}Cs following plant harvest. Thus, phytostabilization can make a significant contribution to environmental management at contaminated sites by helping to minimize the off-site migration of particle-reactive radionuclides through processes of wind and water erosion. In situations where contaminants can be leached from surface soils into groundwater, plants can significantly reduce the flux of infiltrating water, thus reducing the driving force for leaching.

C.2.3 *Chemical Decontamination Technologies or Management Options*

C.2.3.1 *Chelation and Organic Acids*. Chelation is the binding of an organic chemical to a metal ion in such a way that the metal ion can be "enveloped" and removed from its insoluble state (*e.g.*, as an oxide deposit), brought into solution, and hence removed. The organic chemicals, often known as ligands and usually referred to as chelating agents or chelators, tend to have flexible chain structures with more than one site that can strongly interact with the metal ion. The sites on the chelator have an excess of negative charge that bind with the positive charge on the metal ion. Chelation generally is used against fixed contamination rather than smearable contamination, since the latter can usually be removed by simpler means.

There are many potential chelators, each possessing different abilities to bind to different metals. The most common chelators used in decontamination are:

- oxalic acid;
- citric acid;
- gluconic acid;
- ethylenediaminetetraacetic acid;
- hydroxyethylenediaminetriacetic acid;
- ethylenediaminedisuccinic acid;
- oxyethylidenediphosphonic acid; and
- diethylenetriaminepentaacetic acid.

All of the chelators listed above are organic acids. From a chemical perspective, chelators do not have to be organic acids, but this form provides certain advantages. The acid functionality allows the chelator to produce a decontamination outcome similar to that from strong mineral acids. Since many organic acids can be readily oxidized, they can act as reducing agents and bring about decontamination by an oxidation-reduction mechanism as well.

Chelators can be used on a stand-alone basis but are usually employed as part of a more complex or multistage process that combines chelation phenomena with other approaches, such as strong acid dissolution or oxidation reduction. Chelation can be a very effective process, but it is highly dependent on the availability of expert chemical knowledge together with in-depth characterization and knowledge of the system to be decontaminated.

C.2.3.2 *Strong Mineral Acids and Related Materials*. The strong mineral acids used in chemical decontamination are hydrochloric, nitric, sulfuric and phosphoric acids. A strong acid is an acid that ionizes completely or nearly completely in aqueous solution; the concept of strength here does not refer to concentration in aqueous solution. The general basis for the decontamination reaction with simple mineral acids is that the hydrogen ions provided by the acid attack the oxides in the contaminant and destabilize the oxide lattice or the hydrogen ions attack the metal surface directly thus releasing bound contaminants.

The strong mineral acids can be used either by themselves as dilute solutions, in chemical formulations with other materials, or in combination with each other, such as hydrochloric acid/nitric acid (aqua regia). They are flexible, being used as sprays, in dipping processes, or in flushing processes. Their main mode of action is to react with and dissolve metal oxide films that contain contamination, although if used in higher concentrations or at higher temperatures for extended time periods, they can work by dissolving the metal base that underlies a contaminant film. With appropriate care and precautions, they can be used on all metal surfaces except the more reactive metals such as zinc.

C.2.3.3 *Chemical Foams and Gels*. Foams and gels are used as carrier media for other chemical decontamination agents, primarily chelators and acids, and have little inherent decontamination ability on their own. This technique has been widely used in the nuclear industry for large components with complex shapes or large volumes. The foam generating equipment is inexpensive, simple and reliable, and can be used for either manual or remote operation. The detergent part of the foam can have a minor decontamination effect similar to washing with soapy water. However, in the absence of any significant mechanical or scrubbing action to remove particles, detergent foam achieves only minor levels of decontamination.

Foams can be applied to surfaces in any orientation, even on overhead surfaces, and pumped through piping or other closed systems. They produce quite low volumes of secondary waste, and do not produce aerosols associated with aqueous sprays. Their effectiveness comes from the increase in dwell time they permit compared with aqueous solutions. However, since the amount of decontamination agent in contact with the surface is small compared with that of an aqueous solution, repeated applications may be necessary to achieve good levels of decontamination.

C.2.3.4 *Oxidizing and Reducing Agents*. Oxidation and reduction (redox) is the term used for chemical reactions in which one material, the reducing agent, accepts an electron (the reduction process) while another material, the oxidizing agent, donates an electron (the oxidation process).

The concept of oxidation state originates in the question of whether or not a metal atom is attached to an oxygen atom. Unattached neutral atoms of any element, including metals, are said to have an oxidation state of zero. Since oxygen almost always accepts two electrons when it combines with other atoms to make an oxide, the oxygen in the oxide is said to have an oxidation state of minus two. Since electrons are neither consumed nor produced but merely transferred in a chemical reaction, the metal atom in a metal oxide such as iron(II) oxide (FeO) is said to have an oxidation state of plus two. If an oxidizing agent is introduced, the FeO can be oxidized to Fe_2O_3 where the iron now has an oxidation state of plus three; alternatively, if a reducing agent is introduced, the FeO can be reduced to iron where the iron now has an oxidation state of zero.

The ability to control the oxidation state of an element is important because a metal may be more soluble in certain oxidation states than in others, a characteristic that is important to decontamination. Generally, solubility increases with increasing oxidation state, so oxidation tends to be more important in decontamination than reduction. However, reduction of the oxidation state of a metal can be useful if the metal in a lower oxidation state has a stronger binding behavior with a chelator. Sodium hypophosphate and hydrazine have been used as stand-alone reducing agents, while chelating agents such as oxalic and ethylenediaminetetraacetic acids are often used as reducing agents in more complex processes.

In addition to modifying solubility, the ability to control the oxidation state of an element is also important since contaminants are often present as metal oxides. If some of the metal atoms in the oxide lattice can undergo a change in oxidation state, then the lattice may be disrupted and the contaminant may become more easily removed from the surface. This conditioning of the metal oxide is important since it complements the decontamination effects brought about by acids or chelators.

Decontamination by use of an oxidizing agent alone has been performed but is now comparatively rare due to its limited effectiveness compared with the combination of oxidation with other decontamination processes such as acid dissolution or chelation. The most common stand-alone oxidizing agents are bleach (usually calcium or sodium hypochlorite-based compounds), nitric acid, and alkaline-permanganate solutions. Alkaline-permanganate is often used to remove chromium in a corrosion film that harbors radioactive contaminants; the permanganate is a powerful oxidizing agent that oxidizes chromium to Cr_2O_3 which can then dissolve in the alkaline solution as a chromate.

More frequently, oxidation is one step in a more complex process. In recent years, the nuclear power industry has developed a number of such processes aimed at specific, well-defined types of contamination. A number of examples are given in Appendix C.2.3.1 of chelators and organic acids, which are used in the low oxidation state transition metal ion process, the nitrate-oxalic acid process, the decontamination for decommissioning process, the Ontario Power Generation Process, the Canadian Decontamination and Remediation Process, the alkaline-permanganate/sulfamic acid process, and the alkalinepermanganate/oxalic acid process. Other examples are described elsewhere (DOE, 2011; EPA, 2007).

C.2.4 *Physical Decontamination or Management Options*

Physical decontamination can be either an alternative or a complement to chemical decontamination. The performance of a given technology is highly dependent on a variety of factors, including contaminant type, its chemical and physical properties, origin and history, depth of penetration, surface material properties. Treatability and feasibility studies are critically important. If any generalization can be made, it is that operator experience indicates that physical decontamination technologies are best applied to large, regular, unencumbered surfaces. Just as chemical decontamination owes much to experience in industrial cleaning, physical decontamination technologies owe much to industrial surface preparation and finishing experience. Both types of decontamination draw heavily on experience gained in their respective background areas, and both are likely to draw from future technology developments.

Physical decontamination, also referred to as mechanical decontamination, is the removal of surface radioactive contamination by physical processes such as flushing, wiping, brushing, vacuuming, grinding, blasting, scabbling, shaving, spalling, peening, scaling, other forms of scarifying, or the application of strippable coatings.

Physical decontamination techniques can be divided into surface cleaning techniques and surface removal techniques. Surface cleaning techniques include brushing, flushing, strippable coatings, vacuuming, and wiping, where the surface remains intact but contamination on the surface is mechanically dislodged. Surface removal techniques include blasting, grinding, peening, scabbling, scaling, shaving, and spalling, where the contamination is removed by virtue of the removal of an entire layer of the surface. Many of these techniques are described below.

C.2.4.1 *Strippable Coatings*. Strippable coatings are paints, polymers and related coating materials that can be applied to a surface contaminated with loose, removable particulates or loose contaminant-harboring debris. The coatings are allowed to penetrate into microvoids on the surface and adhere to (or mechanically envelop) the contaminants, allowed to set or cure, and then removed bringing the contamination with the coating. Removal of the strippable coating from the surface involves stripping or pulling the coating away from the surface. The coating can be rolled as it is removed for ease of handling and to further trap any residual contamination on the surface of the coating. The coatings are frequently water-based organic polymers to minimize organic vapor releases. The effectiveness of contaminant removal increases as the polymers interlink. The coatings can be applied by spray, brush, roller or squeegee, and to enhance strippability, fiber reinforcement can be added to the polymer mix.

Strippable coatings can be used in three ways:

- decontaminating coating outlined above;
- protective coating applied to uncontaminated surfaces in areas that are liable to contamination; and
- means of fixing loose contamination on surfaces to prevent the further spread of contamination while other operations proceed.

C.2.4.2 *Centrifugal Shot Blasting*. Centrifugal shot blasting is a decontamination technology used to remove paint and light coatings from concrete surfaces or to abrade concrete surfaces directly. Hardened steel shot is rapidly propelled at contaminated surfaces to fracture the surface, resulting in small dust-sized particles that can be vacuumed and removed for proper disposal. Shot blasting, unlike many decontamination technologies, results in a relatively smooth surface that can be recoated and reused.

Centrifugal shot blasting is electrically powered, and can remove light coatings on concrete surfaces up to 1.3 to 2.5 cm deep, though it is ideal for removing surfaces between 1.6 to 3.2 mm in depth. A motorized blast wheel inside the system is supported by a booster motor and fan. Once these components are running, shot is released into the system through a gate from a storage hopper. The speed of the system, the size of the shot, and the amount released into the system can be varied based on the degree of removal necessary.

The shot blast unit relies on a dust collection system to remove abraded dust and particles and to reduce airborne contaminants during the decontamination process. An air wash baffle system separates the reusable shot from the contaminants to cycle back into the system.

In addition, a high-efficiency particulate (HEPA) filtration system, an air compressor, and a generator (125 kW) or power source are required to operate the system.

C.2.4.3 *Concrete Grinder.* The concrete grinder uses a diamond grinding wheel to decontaminate and strip concrete surfaces. The light-weight hand-held device creates a smooth surface when applied to flat or slightly curved surfaces, produces little vibration, and with a vacuum attachment, effectively removes dust created by the grinding process. When used in a circular motion, it rapidly grinds concrete surfaces 1.5 to 3 mm deep. A dust collection shroud is designed to attach to the vacuum hose of an on-site HEPA filtration system, and the vacuum filtration system is required for grinder use. The diamond grinding wheel has external shroud holes which allow air intake to cool the working blades. Air taken in by the external shrouds passes into the internal discharge holes which feed to the vacuum filtration system.

C.2.4.4 *Concrete Shaver.* The concrete shaver is an electrically driven, self-propelled system capable of removing contaminants from concrete floors. It is considered an alternative to the traditional hand-pushed, multi-piston pneumatic scabbler on wheels. The cutting head of a concrete shaver is a drum that contains embedded diamonds. The number of blades chosen is dependent upon the surface finish required. A typical unit weighs ~150 kg, consumes 16 A of 380 to 480 V, three-phase power, and has forward and reverse action. The system can operate in ambient temperatures from 30 to 400 °C. Commercially available concrete shavers are well suited for large, wide-open concrete floors and slabs.

C.2.4.5 *Concrete Spaller.* The concrete spaller is used to decontaminate and strip both slightly curved and flat concrete surfaces. It is effective in large areas, and it is a good tool for hotspots and in-depth decontamination of cracks in concrete. It can also be used to gather samples of concrete to be tested. Holes are drilled in the concrete surface to be decontaminated in a honeycomb pattern, and the spaller bit is inserted into a drilled hole. The four-way hydraulic valve on the hydraulic pump expands the bit in the hole causing the spalling. Chunks of concrete resulting from the spalling are up to 5 mm thick and 18 to 41 cm in diameter and are captured by a metal shroud that is attached around the spaller. A detachable shroud includes a vacuum port which allows a hose to connect to an on-site HEPA filtration system if dust control is necessary.

C.2.4.6 *Dry Ice Blasting*. Dry ice blasting, or carbon dioxide blasting, is an industrial cleaning process for surfaces that uses carbon dioxide pellets as the blasting medium. Carbon dioxide pellets are ~1 to 3 mm in size and are very cold (below –73.3 °C). They are housed in a machine where they are typically accelerated by compressed air with pressures in the range of 100 to 150 psi, although lower and higher pressures of up to 300 psi may be used in certain circumstances.

In dry ice blasting, contamination is removed by three mechanisms that occur nearly simultaneously. First, the accelerated carbon dioxide pellets drive the contamination off of the surface because of their impact at high velocities, similar to that of sandblasting. Second, the cold pellets create a thermal differential with the contaminant material and the surface, causing the contaminant and the surface to contract at different rates, which weakens the bond between them. Finally, the carbon dioxide pellets lift the contamination off of the surface when they rapidly expand into a vapor.

All of these machines operate on the principle that the carbon dioxide gas returns to the atmosphere and leaves only the contaminant and particles removed from the surface as waste. Therefore, they are usually used with other systems that filter the carbon dioxide gas and collect the waste material. In general, dry ice blasting requires superlative off-gas treatment systems and has been described as relatively slow.

C.2.4.7 *Dry Vacuum Cleaning*. Dry vacuuming has been used effectively in radiological surface decontamination of building surfaces, floors, beams, stairs, and other solid media. It generally uses a commercial or industrial grade vacuum with a HEPA filter to remove dust and particles from building and equipment surfaces. The

HEPA filters trap dust and debris to protect against airborne contamination and to prevent recontamination of the air and surfaces just vacuumed. Depending on the nature of the contamination, the dry vacuuming process often occurs in a containment structure, which may consist of two layers of reinforced nylon tied to a self-supported, reusable framework. The floors, walls, and ceiling are often one piece or are sealed to prevent the escape of contaminants.

HEPA vacuuming is ideal for the decontamination of surfaces with loose contamination. The filters remove a minimum of 99.97 % of particulates larger than 0.3 μm. In some commercial models, the HEPA filter is integrated into a "bag-in/bag-out glove-box" assembly that permits removal of spent filters directly into sealable, disposal bags without exposure to the atmosphere. Thus, dry vacuuming may be used as an initial treatment method, possibly followed by another technology for further treatment to reach desired protection levels.

C.2.4.8 *Electro-Hydraulic Scabbling*. Electro-hydraulic scabbling uses a short (microsecond), high current (tens of thousands of amperes), high voltage (tens of thousands of volts) discharge between two electrodes in water to create a plasma bubble and a shockwave capable of scabbling concrete surfaces. A series of discharges repeated at a rate of a few pulses per second are created between electrodes placed close to the concrete surface and under a thin layer of water. The water acts as a medium for transferring the shock and cavitation waves that crack and peel away layers of concrete. The water prevents air breakdown of the wave above the concrete surface, and it eliminates airborne contamination.

The process is a rapid and controllable concrete scabbling technique that generates very little secondary waste. The consumption of water is much lower than in conventional high-pressure, water-jet decontamination techniques. By varying the energy of the pulse, the profile of the pulse, and the total number of pulses at a given location, the depth of scabbling can be controlled. It can be used to decontaminate deeply contaminated concrete floors, walls or ceilings.

C.2.4.9 *En-vac® Robotic Wall Scabbler.* The En-vac® Robotic Wall Scabbler (ERWS) (MAR-COM, Inc., Portland, Oregon) is a remote-controlled grit blasting unit specifically designed to work on flat-surfaced walls. It also is capable of working on floors. The ERWS adheres to walls by high vacuum suction created in a sealed blasting chamber at the unit's base. The vacuum system also serves to prevent any fugitive dust or grit emissions from the working surface of the blasting operation. The unit is supported by a safety harness system and moves horizontally and vertically along floors, walls and ceilings by individually motor-controlled wheels. The complete En-vac® Blasting System consists of the ERWS (the unit that performs the scabbling), a recycling unit, a filter, and a vacuum unit.

The main components of the ERWS are the blast housing, lip seal, four motor and wheel drive-steer assemblies, blast nozzle with oscillator motor, and vacuum control device. The ERWS scabbles by abrasive blasting using abrasive steel grit or steel shot as the surface removal medium. The vacuum unit creates the vacuum that holds the robotic unit to the wall and contains and transports the waste. Recyclable and spent blast grit and blast residue are returned from the robot to the recycling unit through the vacuum hose. Debris from the scabbling operation is processed by a recycling unit, a filter, and a vacuum unit, all of which are separate from the robotic unit. The recycling unit continuously provides abrasive grit to the robot through the blast hose.

C.2.4.10 *Grit Blasting*. Grit blasting is a process where abrasive particles are pneumatically accelerated and forcefully directed against a surface. These high-speed particles can be used to remove contaminants from a surface and to condition the surface for subsequent finishing. Typical grit blasting applications include:

- roughening surfaces in preparation for thermal spraying, painting, bonding or other coating operations;
- removing rust, scale, sand or paint;
- removing burrs;
- providing a matte surface finish;
- removing flash from molded components; and
- cosmetic surface enhancement or etching.

Grit blasting can be used on open surfaces like floors and walls and for awkwardly shaped surfaces like machine parts. The efficiency of the blasting process will depend in part on the abrasive used, on the force with which it is delivered, on the material targeted, and on the characteristics of the surface.

A number of different abrasive materials are commercially available. Traditionally, the metal grit used in grit blasting consisted of iron or aluminum oxide, but many crushed or irregular abrasives are now used. There are some restrictions on the type and chemical characteristics of abrasive materials that may be used. Restricted substances include any substance that consists of or contains 2 % or more dry weight of crystalline silicon dioxide. Common substances that fall in this category are river sand, beach sand, white sand, pool filter material, and dust from quartz rock. Also restricted are substances that contain more than 0.1 % antimony, 0.1 % arsenic, 0.1 % beryllium, 0.1 % cadmium, 0.5 % chromium, 0.5 % cobalt, 0.1 % lead, 0.5 % nickel, or 1 % tin.

Other abrasive materials are also available. Glass grit, which is recycled glass particles, comes in a variety of grades. It is reported to be nontoxic and inert, thereby reducing the likelihood of respiratory and environmental problems. It is chloride and salt-free, which leads to less corrosion on prepared surfaces; it is reported to have the ability to cut and/or clean many different surfaces efficiently; and it has lower disposal costs than some other abrasive materials.

C.2.4.11 *High-Pressure Water.* Simple flushing with water is the most basic approach to radiological surface decontamination. Soluble contaminants are dissolved and unbound particulates are dislodged and carried away. Increased pressures and flow-rates enhance the mechanical effects of the water stream, allowing more strongly bonded particulates or those trapped in surface occlusions to be removed and also allowing other surface material such as paint layers and other debris to be stripped. As the pressure increases, the ability to remove surface material increases until, at pressures of ~50,000 psi, substances such as concrete can be damaged and, if abrasives are added, metal can be cut.

The technique is known by a variety of names depending on the pressure range being used. Common terms include water flushing (low pressures), hydroblasting, hydraulic blasting, hydrolasing (up to ~15,000 psi), high-pressure water jetting, ultra-high-pressure water jetting, and water jet cutting (up to ~50,000 psi). The pressure range and flow rates chosen are usually optimized for the specific situation. For example, a corrosion deposit on a metal surface may require a higher pressure but lower flow rate than removal of paint from a concrete surface. In all cases the wastewater is collected and filtered, with the filtered water either being further treated for soluble material or recycled prior to final treatment to reduce both water consumption and the total waste volumes.

In the hands of a skilled user, the technique is very effective. Coatings and deposits, even galvanized layers, can be removed without damaging the underlying base metal. Typical decontamination applications include the cleaning of inaccessible surfaces such as the interiors of pipes, structural steel work, cell interiors and surfaces too large for regular scrubbing.

C.2.4.12 *Soft Media Blast Cleaning (sponge blasting).* Soft media blast cleaning uses the kinetic energy of soft media to abrade a surface and absorb contaminants. Soft media are propelled by compressed air against the surface to loosen, remove and absorb contaminants in a recyclable media matrix that disintegrates over time. Due to the soft nature of the media, there is little to no bounce back from the surface. The air compressor is the only component not provided as a part of the technology, but it is required to provide the system with clean, dry air, 7.1 m^3 min^{-1} flow rate, and 120 psi pressure line at the feed unit.

Compressed air flows into a feed unit with two mechanisms: an actuator which stirs the media to ensure an even dispersion, and an auger which limits the amount of media fed into the air stream. Feed units are portable and vary in size, according to user requirements. A standard hose 2.5 cm in diameter and up to 7.5 m long delivers the media air stream through a venturi-style tungsten carbide blast nozzle. The system comes with a "dead-man" auto-shut-off switch. Nozzles can vary in diameter size to accommodate larger surface areas or smaller more difficult to clean areas. There are several types of media impregnated with a range of abrasives (*e.g.*, steel, garnet, plastic, and aluminum oxide) to be used for different types of surface cleaning and decontamination.

C.2.4.13 *Steam Vacuum Cleaning*. Steam vacuum cleaning is similar to high-pressure water cleaning systems in that it uses the kinetic energy of a fluid to mechanically dislodge contaminants from a surface. However, in addition to the kinetic energy that arises directly from the impulse of the fluid striking the surface, there is an extra effect due to the flashing of superheated water into steam. The superheated water is delivered to the target surface, where it flashes to steam upon impact, and dislodges contaminants. The hood of the steam/vacuum cleaning head traps and collects the dislodged contaminants, steam and water droplets. The waste stream passes through a vacuum recovery subsystem that discharge clean air to the atmosphere. A detergent may be added to the pressurized water stream to improve washing effectiveness.

C.2.4.14 *Piston Scabbler.* Piston scabblers are designed to scarify concrete floors and slabs without generating large amounts of airborne contamination. In typical mechanical scabbling, the floor is fractured by a piston or series of pistons attached to the scabbling head. The pulverized concrete is vacuumed up as the head operates, and the waste material is stored in a drum assembly for later disposal.

C.3 Decontamination Technologies or Management Options for Contaminated Media

The following paragraphs briefly describe the decontamination technologies or management options for contaminated media that may be considered in a large-scale environmental cleanup effort. Many technologies are effective in different environments (temperatures) and media (*e.g.*, soils or water). The specific application of each technology may be inherent in its use (*e.g.*, phytoremediation for agriculture land) or be applied based on its ability to be implemented in the field (*e.g.*, land encapsulation for hazardous materials). Where possible, a target application is provided in the description of each technology. Detailed information about applicable site characteristics, waste management issues, operating characteristics performance data, capital and operating costs, and commercial availability are provided elsewhere (EPA, 2007). A qualitative rating attempts to summarize this information in Appendix C.4.

C.3.1 *Decontamination Technologies or Management Options for Contaminated Soils*

C.3.1.1 *Capping*. Capping can be used to contain all types of waste. It is a containment technology that forms a barrier between the contaminated media and the surface, thereby shielding humans and the environment from exposure to radiation. Capping radioactive waste involves covering the contaminated media with a cap sufficiently thick and impermeable to minimize the migration of waste to the surface and to control windblown contamination. A cap must also restrict surface water infiltration into the contaminated subsurface to reduce the potential for contaminants to leach from the site. Capping does not prevent horizontal migration of contaminants due to groundwater flow; however, it can be used in conjunction with vertical walls to produce an essentially complete structure surrounding the waste mass (Eckerman *et al.*, 1988). This complete type of containment is referred to as land encapsulation and is discussed in Appendix C.3.1.2.

Caps can be made of a variety of materials, each of which provides a different degree of protection. These materials include synthetic membrane liners such as geomembranes (*e.g.*, high-density polyethylene), asphalt, cement, and natural low-permeability soils such as clay. A cap is usually a combination of materials layered one on top of the other. A typical cap for containing radioactive media might consist of ~1 m of compacted filler, a geomembrane, a layer of compacted clay, another geomembrane, and ~1 m of topsoil. A layer of ground cover vegetation can be applied to the surface of the cap to reduce soil erosion and limit the potential for precipitation to permeate the cap. A drainage layer can also be necessary beneath the topsoil and above the upper geomembrane in areas of higher precipitation.

Evaluations of existing capping systems have shown that capping is an effective containment system if properly designed and installed (EPA, 1998). Site-specific conditions such as climate need to be considered in determining an appropriate cap design. Many alternatives are possible, depending on the need for water control at the site. Software programs such as the hydrologic evaluation of landfill performance model have been developed to assist site managers in barrier design and performance (Schroeder *et al*., 1994).

C.3.1.2 *Land Encapsulation*. Land encapsulation generally is used as a final disposal method. Thus, it can be applied to a wide variety of contaminants, including LLRW or mixed and commercial waste. Land encapsulation might be appropriate for radionuclides, whether or not they have been extracted from a contaminated medium. Currently, no commercial operating land encapsulation facilities accept high-level waste.

Land encapsulation is a well-proven and readily implementable containment technology that is generally used at the final disposal stage of radioactive waste management (DOD, 1994). Other technologies are often used to reduce the volume of the radioactive waste, after which land encapsulation is used to contain and immobilize the treated waste. On-site land encapsulation involves excavating the disposal area and installing a liner or other impermeable material in the excavated area. Radioactive waste and/or residuals requiring disposal are then transported and backfilled into the lined, excavated area and an appropriate cap is applied. While land encapsulation can occur on-site, most waste is transported to off-site land encapsulation facilities.

Facility design guidelines developed by EPA and NRC for commercial, mixed LLRW disposal facilities include two or more composite liners (*e.g*., upper geomembrane and compacted soil layer) and a leachate collection system located above and between the liners. The facility design minimizes water contact with the encapsulated waste as required by NRC (2004).

Obtaining necessary approvals to dispose of radioactive waste on-site using land encapsulation can be very difficult. However, the Low-Level Radioactive Waste Policy Amendments Act of 1985 requires states and compacts to develop siting plans for LLRW disposal facilities (NRC, 2002). A remote area dedicated by a state or other government entity to radioactive waste containment could also receive waste from other sources within and outside that jurisdiction, given the appropriate approvals.

C.3.1.3 *Cryogenic Barrier.* Refrigeration has been used to freeze soils in large-scale engineering projects for over 40 y. In the last two decades, this technology has been examined as a containment method for subsurface radionuclide contamination. A cryogenic barrier provides containment by freezing contaminated subsurface soils to create an ice barrier around a contaminated zone. This barrier reduces the mobility of radionuclide contaminants by confining the materials and any contaminated groundwater that might otherwise flow through the site.

To create a typical cryogenic barrier, rows of freeze pipes are inserted in an array outside and beneath the contaminated zone. The first row of freeze pipes is installed around the circumference of the site at angles below the contaminated zone; the second set of freeze pipes is installed a set distance away from the first row. Careful installation of the piping is necessary to ensure complete barrier formation. Once installed, the array of pipes is connected *via* a manifold to a refrigeration plant. In a completely closed system, the pipes carry a coolant that freezes the inner volume between the two rows of freeze pipes to create the ice barrier. Coolants typically consist of salt water, propylene glycol, or calcium chloride. Soil moisture content of 14 to 18 % is considered optimal for implementing the cryogenic barrier. At higher moisture contents, the power costs to form the barrier increase since there is more water volume to freeze (EPA, 2007). At lower moisture contents (such as in arid regions), additional moisture might have to be introduced to form the barrier (Pearlman, 1999).

Cryogenic barriers provide subsurface containment for a wide variety of waste in soil and groundwater, including radionuclides, metals and organics. Because containment by other barrier methods such as grout curtains and slurry walls becomes more cost-effective after 8 or 9 y of operation, cryogenic barriers might be more applicable to containment of shorter-lived radionuclides such as tritium (DOE, 1999; Pearlman, 1999).

C.3.1.4 *Vertical Barriers*. A vertical barrier is a containment technology that is installed around a contaminated zone to help confine radioactive waste and any contaminated groundwater that might otherwise flow from the site. Vertical barriers also divert uncontaminated groundwater flow away from a site. To be effective, vertical barriers must reach down to an impermeable natural horizontal barrier, such as a clay zone, in order to effectively impede groundwater flow. This technology is often used when the waste mass is too large to treat in a practical manner and where soluble and mobile constituents pose an imminent threat to a drinking water source. Vertical barriers are frequently used in conjunction with a surface cap to produce an essentially complete containment structure (Eckerman *et al*., 1988; IAEA, 1999).

Three types of vertical barriers used to contain radioactive waste are slurry walls, grout curtains, and sheet pile cutoff walls.

Slurry walls are subsurface barriers that consist of a vertically excavated trench filled with slurry. The slurry both hydraulically shores the trench to prevent the collapse of the side walls during excavation and produces a barrier to groundwater flow. The slurry is generally a mix of soil, bentonite and water or cement, bentonite and water. Soil-bentonite slurry walls have a wider range of chemical compatibility and lower permeability than cement-bentonite slurry walls, but are less strong and more elastic (IAEA, 1999; 2001). If greater strength is required or if chemical incompatibilities between bentonite and site contaminants exist, other slurry wall compositions can be used such as pozzolan/bentonite, attapulgite, organically-modified bentonite, or slurry/geomembrane composites (FRTR, 2002a).

Grout curtains are thin, vertical grout walls installed in the ground. They are constructed by pressure-injecting grout directly into the soil at closely spaced intervals around the waste site. The spacing is selected so that each "pillar" of grout intersects the next, thus forming a continuous wall or curtain (Eckerman *et al.*, 1988). Grout curtains can be used up-gradient of the contaminated area, to prevent clean water from migrating through waste, or down-gradient, to limit migration of contaminants. Grout curtains are generally used at shallow depths (*i.e.*, 9 to 12 m maximum depth). In some situations, grout curtains can be used where slurry walls are impractical, such as installing a barrier up a slope or at an angle (Gerber and Fayer, 1994) and where a barrier needs to be installed in rock (LaGrega *et al.*, 2000).

Sheet pile cutoff barriers are constructed by driving interlocking steel or high-density polyethylene into the ground. The joints between individual sheets are typically plugged with clay slurry (for steel sheets) or an expanding gasket (for high-density polyethylene sheets). The steel piles can be driven directly into the ground, while the synthetic piles need to be driven with a steel backing that is removed once the synthetic sheet is in place. Sheet piling has been considered a less permanent measure than slurry walls or grout curtains because of unpredictable wall integrity (IAEA, 1999; 2001), but recent developments including improvements in sheet interlock design and innovative techniques to seal and test the joints between the sheets has improved performance (EPA, 1998).

C.3.1.5 *Cement and Chemical Solidification and/or Stabilization*. Solidification and/or stabilization technologies reduce the mobility of hazardous and radioactive contaminants in the environment through both physical and chemical processes. Stabilization seeks to trap contaminants within their "host" medium, by inducing chemical reactions between the stabilizing agent and contaminants. Solidification encapsulates the waste in a monolithic solid of high structural integrity. Solidification does not involve chemical interaction or chemical bonds between the contaminants and the solidification agents but bonds them mechanically. Solidification and stabilization techniques are often used together. While the contaminants would not be removed and would remain radioactive, the mobility of the contaminants would be eliminated or reduced.

Solidification/stabilization has been implemented full-scale and can be employed *in situ* or *ex situ*. *In situ* techniques use auger/caisson systems and injector head systems to apply agents to soils in place. *Ex situ* techniques involve digging up the materials and machine-mixing them with the solidifying agent rather than injecting the agent to the materials in place. *Ex situ* processes typically require disposal of the resultant materials. *In situ* and *ex situ* techniques can be used alone or combined with other treatment and disposal methods to yield a product or material suitable for land disposal or, in other cases, that can be applied to beneficial use. Each technique has been used both as an interim and final remedial measure.

Cement solidification/stabilization processes involve the addition of cement or a cement-based mixture that limits the solubility or mobility of the waste constituents. Types of solidifying and/or stabilizing agents include Portland cement, gypsum, and pozzolanic-based materials such as fly ash, blast furnace slag, kiln dust, and pumice. These types of cements are also referred to as hydraulic cements because they all require the addition of water for curing and setting.

Chemical solidification and/or stabilization involves adding chemical reagents to waste in order to limit the waste solubility and mobility. Chemical solidification and/or stabilization agents include thermoplastic polymers (asphalt bitumen, paraffin, polyethylene, polypropylene, modified sulfur cement), thermosetting polymers (vinyl ester monomers, urea formaldehyde, epoxy polymers), and some other proprietary additives. Like cement-based solidification/stabilization applications, the chemical-based methods can increase the volume of the resulting solidified and/or stabilized mass. However, because the waste is dried before applying *ex situ* chemical methods and because *in situ* thermosetting methods are efficient in filling void spaces, the increases in volume are less than those for cement-based methods in most cases (EPA, 2007).

C.3.1.6 *Solvent/Chemical Extraction*. Solvent/chemical extraction is an *ex situ* chemical separation technology that separates hazardous contaminants from soils, sludges and sediments to reduce the volume of hazardous waste that requires treatment. Solvent/chemical extraction involves excavating and transferring soil to equipment that mixes the soil with a solvent. Use of water alone as the solvent is referred to as soil washing (EPA, 2007).

The solvent/chemical extraction equipment can handle contaminated soil either in batches of dry soil, or as a continuous flow for pumpable waste. When the hazardous contaminants have been sufficiently extracted, the solvent is separated from the soil and is either distilled or removed from the leachate. Distilled vapor consists of relatively pure solvent that is recycled into the extraction process; the liquid residue, which contains concentrated contaminants, undergoes further treatment or disposal. If the contaminants are precipitated, the sludge is dried with a filter press. While not all radionuclides and solvent will be removed from the contaminated soil, if it is sufficiently clean it can be returned to its original location. Otherwise, it might require separate storage or disposal.

Solvents that could be used to remove radioactive waste include: complexing agents, such as ethylenediaminetetraacetic acid; inorganic salts; organic solvents; and mineral acids, such as sulfuric, hydrochloric or nitric acid. Each solvent's effectiveness in removing different contaminants depends on concentrations, pH, and solubility (DOD, 1994; Eckerman *et al*., 1988).

Solvent/chemical extraction is commonly used with other technologies, such as solidification/stabilization, incineration, or soil washing, depending on site-specific conditions.

C.3.1.7 *Dry-Soil Separation*. Dry-soil separation separates radioactive particles from clean soil particles and can reduce the volume of radioactive waste by >90 %. The simplest application involves screening and sieving soils to separate finer fractions (silt and clay) from coarser fractions of the soil. Since most contaminants tend to bind, either chemically or physically, to the fine fraction of a soil, separating the finer portion of the soil can concentrate the contaminants into a smaller volume of soil for treatment or disposal (FRTR, 2002b).

In a refinement of this process, radiation detectors are used to further separate materials (segmented gate system). For this method, radionuclide-contaminated soil is first excavated and screened to remove large rocks and debris. Large rocks are crushed and placed with soil on a conveyor belt, which carries the soil under radiation detectors that measure and record the level of radiation in the material. Radioactive batches of material on the conveyor belt are tracked and mechanically diverted through automated gates, which separate the soil into contaminated and clean segments. The contaminated materials can be further processed and/or disposed.

C.3.1.8 *Soil Washing*. Soil washing is a process in which water, with or without surfactants, mixes with contaminated soil and debris to produce a slurry feed. This feed enters through a scrubbing machine to remove contaminated fine soil particles (silts and clay) from granular soil particles. Contaminants are generally bound more tightly to the fine soil particles and not to larger grained sand and gravel. Soil washing is most effective when the contaminated soil consists of <25 % silt and clay and at least 50 % sand and gravel; soil particles should be 0.25 to 2 mm in diameter for optimum performance. Separation processes include screening to divide soils into the coarse and fine fractions, and dissolving or suspending contaminants in the wash. The sand and gravel fraction is generally passed through an abrasive scouring or scrubbing action to remove surface contamination. The fine fraction can be separated further in a sedimentation tank, sometimes with the help of a flocculating agent. The output streams of these processes consist of clean granular soil particles, contaminated soil fines, and process/wash water, all of which are tested for contamination.

Soil washing is effective only if the process transfers the radionuclides to the wash fluids or concentrates them in a fraction of the original soil volume. In either case, soil washing must be used with other treatment technologies, such as precipitation, filtration, and/or ion exchange. Clean soil (sand and gravel) can be returned to the excavation area, while remaining contaminated fine soil particles and process waste are further treated and/or disposed (Luftig and Weinstock, 1997). Despite many bench and pilot tests, soil washing has not been fully demonstrated as a technology for reducing the volume of radioactively-contaminated soil.

C.3.1.9 *Flotation*. Flotation separates radionuclide-contaminated soil fractions (usually the fine soil particles such as silts and clays) from the clean soil fractions (large granular soil particles and gravel) in order to reduce the volume of soil requiring treatment or disposal. During flotation, contaminated soil is pretreated to remove coarse material and then mixed with water to form a slurry. A flotation agent (a chemical that binds to the surface of the contaminated soil particles to form a water repellent surface) is then added to the solution. Small air bubbles are then passed through the slurry. These air bubbles adhere to the floating particles, transport them to the surface, and produce a foam containing the radionuclide-contaminated soil particles. The foam is mechanically skimmed from the surface or allowed to overflow into another vessel, where it is collected for treatment and/or disposal. After dewatering and drying, the clean soil can then be returned to the excavation area. Flotation can be performed in a stationary column or rotating vessel, using centrifugal force to enhance the process (Misra *et al*., 2001). Contaminants that can potentially be treated using flotation include heavy metals, such as lead and mercury, and radionuclides such as uranium, plutonium, thorium and radium.

C.3.1.10 *In Situ and Ex Situ Vitrification*. Vitrification involves heating contaminated media to extremely high temperatures, then cooling them to form a solid mass. Upon cooling, a dense glassified mass remains, trapping radioactive contaminants. The process can be applied to contaminated soil, sludge, sediment, mine tailings, buried waste, and metal combustibles. Vitrification technologies can be particularly useful for treating radioactive or mixed waste and is the treatment of choice for high-level radioactive waste. EPA has designated vitrification as a "best-demonstrated available technology" for high-level waste (EPA, 2005; 2007).

Vitrification processes can be performed both *in situ* and *ex situ*. *In situ* vitrification can operate at a higher temperature than most *ex situ* melters and produces a product that has more resistance to leaching and weathering (Luftig and Weinstock, 1997). This technology is currently available on a commercial scale. Although mobility is greatly reduced for contaminants trapped within the vitrified mass, the activity of contaminants is not reduced. Because of the high temperature of the melt, no residual organic contamination remains in the glass monolith. Upon cooling there is a net volume reduction of the treated material. During all *ex situ* vitrification processes, volatiles are released and organics are either pyrolyzed or oxidized. Therefore, systems for off-gas capture and treatment are necessary to minimize air emissions. After treatment with *ex situ* vitrification, volume reductions of waste can range as high as 80 %, depending on waste type (ACOE, 1997).

C.3.2 *Decontamination Technologies for Liquids*

Chemical separation technologies for liquid media involve processes that separate and concentrate radioactive contaminants from ground, surface, or wastewater. Extractability rates of the different chemical separation technologies vary considerably based on the types and concentrations of contaminants, as well as differences in methodology. Whether these technologies are applicable at a specific site will be determined by site-specific factors.

Chemical separation technologies can be *in situ* or *ex situ*. For *ex situ* treatment of groundwater, the construction and operation of a groundwater extraction and delivery system is required. All *ex situ* chemical separation technologies generate a treated effluent and a contaminated residual that requires further treatment or disposal. The following decontamination technologies or management options summarized below include:

- ion exchange;
- chemical precipitation;
- permeable reactive barriers;
- membrane filtration;
- adsorption; and
- aeration.

C.3.2.1 *Ion Exchange*. Ion exchange, a fully-developed chemical separation process, is highly efficient in reducing radionuclide and inorganic metal levels in liquid waste streams to levels suitable for effluent discharge. Ion exchange has been identified as a best-demonstrated available technology for the removal of ^{226}Ra, ^{228}Ra, and uranium. This technology separates and replaces radionuclides in a waste stream with relatively harmless ions (*e.g.*, sodium) from a synthetic resin or natural zeolite (for strontium and cesium). Resins consist of an insoluble structure with many ion transfer sites and an affinity for particular kinds of ions. "Exchangeable" ions are bound to the resin with a weak ionic bond. If the electrochemical potential of the ion to be recovered (contaminant) is greater than that of the exchangeable ion, the exchange ion goes into solution and the ionic contaminant binds to the resin. Resins must be periodically regenerated by exposure to a concentrated solution of the original exchange ion. Zeolites, when spent, are stored as solid waste.

A typical ion exchange unit uses columns or beds containing the exchange resin and various pumps and piping to carry the waste streams and potentially new and spent resin. Resins are either acid-cationic (for removing positively-charged ions) or base-anionic (for removing negatively-charged ions); resins used for radioactive liquid waste are often either hydrogen- or hydroxyl-based. Alternatively, some ion exchange units send water through a mixed-bed, which contains both cationic and anionic resins in the same bed (DOD, 1994). Typically, four operations are carried out in a complete ion exchange cycle: service, backwash, regeneration and rinse. In the service step, the ion exchange resin is contacted with the solution containing the contaminant ion targeted for removal. After a critical relative concentration of contaminant ion to exchangeable ion in solution is reached, the resin is spent or no longer effective. A backwash step is then operated to expand the resin and remove fine particles that could be clogging the bed.

Following the backwash, the spent resin is regenerated by exposing it to a very concentrated solution of the original exchange ion, resulting in a reverse exchange process. The rinse step removes excess regeneration solution before the next service step (ORNL, 1994). Regeneration of cationic resins uses acidic solutions, while anionic resins use caustic solutions. The brine from the back-wash, regeneration and rinse steps is collected for radiological waste disposal.

Ion exchange significantly reduces contaminant mobility by immobilizing it in the exchange media, but does not affect the biological effectiveness of the contaminant. It is most effective when the waste stream is in the ionic form; nonionic waste streams or waste streams with suspended solids must be pretreated. Both concentrated waste removed from the resin and spent resin itself must be treated, stored, or disposed of. Also, this technology's effectiveness depends on the pH, temperature, contaminant concentration, and flow rate of the waste material, and the resin's selectivity and exchange capacity. If more than one radioactive contaminant is present, more than one resin or more than one treatment process might be required.

C.3.2.2 *Chemical Precipitation*. Chemical precipitation converts soluble radionuclides to an insoluble form through a chemical reaction or by changing the solvent's composition to diminish solubility. Precipitation adds a chemical precipitant to the radionuclide-containing aqueous waste in a stirred reaction vessel. Solids are separated from the liquids by settling in a clarifier and/or by filtration. Flocculation can be used to enhance removal of solids. Commonly used precipitants include carbonates, sulfates, sulfides, phosphates, polymers, lime, and other hydroxides. The amount of radionuclides that can be removed from a solution depends on the precipitant and dosage used, the concentration of radionuclides present in the aqueous waste, and the pH of the solution. Maintaining optimum pH levels within a relatively narrow range is usually necessary to achieve adequate precipitation.

Either batch reactors or continuous flow designs can be used. Batch reactors are generally favored for flows up to 189,250 L d^{-1} (*i.e.*, 50,000 gallons d^{-1}) and usually operate with two parallel tanks. Each tank acts as a flow equalizer, reactor and settler, thus eliminating the need for separate equipment for each step. Continuous systems have a chemical feeder, flash mixer, flocculator, settling unit, filtration unit, and a control mechanism for feed regulation.

Chemical precipitation significantly reduces the volume of contaminants in the liquid medium and the toxicity of the liquid medium, but not the mobility of the contaminants remaining in the liquid medium (EPA, 2007).

C.3.2.3 *Permeable Reactive Barriers*. Permeable reactive barriers, also known as passive treatment walls, are installed in the subsurface across the flow path of a radioactively-contaminated groundwater plume, allowing the groundwater to flow passively through the wall while prohibiting the movement of the radionuclides. This is accomplished by employing treatment agents within the wall such as chelators, sorbents, and reactive minerals. The radionuclides are retained in a concentrated form by the barrier material, which can require periodic replacement (FRTR, 2002c).

A permeable reactive barrier is built by excavating a trench perpendicular to the groundwater flow path and backfilling it with the reactive materials, which can be mixed with sand to increase permeability. In some applications, the permeable reactive barrier is made the focal point of laterally connected, impermeable subsurface barriers (such as sheet piles or slurry walls) or permeable conduits (such as French drains) so that the groundwater is collected and funneled through the reactive material. This type of arrangement is usually referred to as a funnel and gate system.

Typical permeable reactive barriers are installed to depths of up to ~25 m with backhoes, modified backhoes, and continuous trenching machines. For backhoe excavation in unstable soils, steel sheet piling is sometimes emplaced prior to excavation. Trench boxes are also used to provide stability during backfilling of excavations with the reactive media (EPA, 2007).

Excellent removal of uranium by permeable reactive barriers has been demonstrated using zero valent iron as the reactive media (IAEA, 2004b). Strontium-90 and ^{137}Cs have been reduced in groundwater using chabazite zeolite as the reactive media (ORNL, 1994). Clinoptilolite zeolite as the reactive media has shown high sorption capability for ^{137}Cs, ^{90}Sr, ^{60}Co, and ^{226}Ra (IAEA, 2003).

C.3.2.4 *Membrane Filtration*. Membrane filtration uses a semipermeable membrane to separate dissolved radionuclides or solid radionuclide particles in liquid media (*e.g.*, groundwater, surface water) from the liquid media itself. Generally, some form of pretreatment (such as filtration of suspended solids) is required in order to protect the membrane's integrity. Water flow rate and pH should be controlled to ensure optimum conditions. Two types of membrane processes used for treatment of radionuclides in liquids are micro- or ultrafiltration and reverse osmosis. Both rely on the pore size of the membrane, which can be varied to remove particles and molecules of various sizes. Micro-, ultra- and nanofiltration processes generally work best for separating very fine particles (1 to 100 nm) from the liquid. These filtration processes can operate at pressures in the range of 5 to 100 psi (ACOE, 1997). Efficiencies of ultrafiltration separation are sometimes enhanced through pretreatment of the contaminated liquids with complexing agents to form larger molecular complexes (*e.g.*, metal-polymers or chelates) that are more readily separated by the membranes (Davies and Page, 2000).

Reverse osmosis uses a selectively permeable membrane that allows water to pass through it, but which traps radionuclide ions on the concentrated, contaminated liquid side of the membrane. Normally, osmotic pressures would draw the cleaner water to the dissolved ions, but high pressure in the range of 200 to 400 psi applied to the solution forces water with lower ion concentrations through the membrane (ACOE, 1997). The three most commonly used reverse osmosis membrane materials are cellulose acetate, aromatic polyamide, and thin-film composites, which consist of a thin film of a salt-rejecting membrane on the surface of a porous support polymer.

Membrane filtration processes can treat a variety of waste, including metals and organics, and effectively remove most radionuclides from water. However, tritium cannot be removed easily because of its chemical characteristics. In France, treatment of liquid LLRW containing cobalt and cesium has been performed using ultrafiltration (ACOE, 1997). Reverse osmosis has been identified as a best-demonstrated available technology for the removal of ^{226}Ra, ^{228}Ra, and uranium. EPA has also identified reverse osmosis as an effective treatment for beta-particle emitters such as ^{137}Cs, ^{89}Sr, and ^{131}I (EPA, 1993).

C.3.2.5 *Adsorption*. Liquid-phase carbon adsorption involves pumping groundwater through a series of vessels containing granular activated carbon. Dissolved contaminants in the groundwater are adsorbed by sticking to the surface and within the pores of the carbon granules (EPA, 2001). Activated carbon is an effective adsorbent because of its large surface to mass (volume) ratio of 297 to 2,509 m^2 gm^{-1} of carbon (EPA, 2007). Although granular activated carbon is the most common adsorbent used, other adsorbents include activated alumina, forager sponge, lignin adsorption/sorptive clay, and synthetic resins (FRTR, 2002d). The two most common reactor configurations for carbon adsorption systems are the pulsed or moving bed and the fixed bed. The fixed bed configuration is the most widely used for adsorption from liquids (FRTR, 2002d).

Granular activated carbon can be used to treat organics, certain inorganics, and radionuclides such as uranium, ^{60}Co, ^{106}Ru, ^{226}Ra, and ^{210}Po (Annanmaki and Turtiainen, 2000; Sorg, 1988). Activated carbon is also effective at removing radon from groundwater

(Annanmaki and Turtiainen, 2000; EPA, 2007) but has not been promoted for municipal water systems because the buildup of radon progeny can be significant enough to cause radiation hazards (EPA, 1993). Activated alumina has been shown to be effective in the adsorption of uranium and radium (EPA, 1993).

C.3.2.6 *Aeration*. Aeration is a mass-transfer process that enhances the volatilization of compounds from water by passing air through water to improve the transfer between air and water phases. EPA has identified aeration as a best-demonstrated available technology for the removal of radon (EPA, 1993). The process can be performed using packed towers, tray aeration, spray systems, or diffused bubble aeration. Detailed descriptions of these technologies are provided elsewhere (EPA, 2007; SAIC, 1999).

Aeration treatment of radon-contaminated groundwater produces radon air emissions from the treatment unit. Depending on the radon concentration in the emissions and the applicable regulations, an off-gas treatment system to capture the radon might be needed. Radon off-gas removal usually consists of passing the air emissions through vapor-phase activated carbon treatment.

C.4 Options for Cleanup

In Table C.1, qualitative indicators provide a subjective rating on the potential applicability of the decontamination technologies or management options for large-scale environmental cleanups following a radiological incident contaminating tens to thousands of square kilometers. They may not be applicable to a specific scenario or scenarios with small areas that are easily controlled because the various rating criteria are greatly affected by the size of the scenario. *Urban applications* ratings were based on various parameters such as availability of the technology for large-scale use, and ability to be used on several different surface types or media. *Waste issues* ratings were based on the volume and type of waste generated, including challenges associated with containing or treating generated waste from the specific technology or management option. *Operational issues* ratings were based on several factors including:

- whether a skilled or unskilled labor force is required;
- applicability to various environmental conditions (*e.g.*, temperature limitations);
- known decontamination factors;
- decontamination rates;
- health and safety issues to the workers and members of the public; and
- applicability on different surface types or media.

TABLE C.1—*Decontamination technologies applicable to urban environments following large-scale radiological incidents.*[a]

Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
NO ACTION					
1. *No Active Decontamination Takes Place* Relies on natural attenuation through radioactive decay and weathering processes		●	●	●	●
• implementing cleanup may be perceived as indicating that there is a problem even if doses are low and cleanup is being undertaken to provide reassurance. • perception of affected area from outside may be better (*i.e.*, accident is not perceived as a real problem); people are living normally; economic blight may be less • sends out a clear message that risks are low and so no cleanup is justified; builds public confidence in local authorities; saying risk low and still doing cleanup may give out a mixed message • no cleanup waste is produced • if cleanup is implemented, members of the public may be reluctant to return to their homes • aids return to "normal living" in the area (*i.e.*, to a situation where people can live without the accident/contamination being at the forefront of their minds)	• requires very good communication with the community in order to explain the decision not to cleanup (*i.e.*, justifying that risks are low) • cleanup is visible and may provide reassurance to people inside and outside the contaminated area • needs linking with a very rigorous monitoring strategy • not necessarily good to be seen to be doing no visible cleanup; may send out a message that the local authorities and other organizations do not care enough about the community • need to define the boundary of the area that is not being cleaned up • if food restrictions are in place, there will need to be careful explanation of why this action is required but in other areas like residential areas, no action is taken				
SURFACES, BIOLOGICAL					
2. *Microbiological Effects* Alters the distribution or mobility of the contaminant in soils or sediments		○	—	—	—
• facilitates breakdown of toxic materials	• indirect effect on radionuclide concentrations in soil by potentially altering their availability or mobility				

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
3.	*Phytoextraction* Natural uptake of the contaminant in plants		◒	◒	◒	◒
	• relies on natural uptake of vegetation to remove contaminant from soils • minimizes ecosystem disturbance • minimizes cleanup costs • "hands-off" approach so worker exposure should be reduced, chance of accidents should be reduced, and safety should be improved	• handling biomass waste • increases radionuclide available to materials that can be redistributed unless managed properly • long recovery period required • certain plant species may not grow in the impact environments • effectiveness is heavily dependent on soil condition (*e.g.*, potassium, ammonia concentrations) • constant monitoring of the slow process				
4.	*Phytostabilization* Reduces migration of contaminant		◒	●	◒	◒
	• reduces migration of radionuclides • reduces soil erosion • may be used as a boundary around an area treated with phytoextraction methods • "hands-off" approach so worker exposure should be reduced, chance of accidents should be reduced and safety should be improved	• does not remove contaminant from soil • relies on natural attenuation from decay or erosion • long recovery period with potential land restrictions				

SURFACES, CHEMICAL

5. *Chelation or Organic Acids*
Organic chemical binds to a metal ion to move it to a soluble state for removal.

● ○ ○ ○

- strongly bonds to metal ions
- can be tailored to specific radionuclides
- prevents/reduces redeposition
- carbon, hydrogen, oxygen chelators produce carbon dioxide and H_2O in waste stream
- easily applied
- effective on complex geometries
- reaches areas only accessible by liquids
- readily available from a large number of suppliers

- mobilizes the contaminate
- waste management issues (primary and secondary forms)
- concentrates radionuclides leading to increased exposure potentials
- requires chemical expertise
- lower quality of performance than other technologies
- surface pretreatments may be needed
- temperature dependency
- contact time issues

6. *Strong Mineral Acids*
React with and dissolve metal oxides to enhance removal.

◒ ○ ◒ ○

- strongly bonds to metal ions
- flexible (sprays, dipping or flushing processes)
- effective on complex geometries
- reaches areas only accessible by liquids
- quick and effective
- readily available from a large number of suppliers

- health and safety issues paramount (creating explosive or poisonous gases)
- mobilizes the contaminant
- waste management issues (must neutralize)
- difficulty in controlling reactions
- concentrates radionuclides leading to increased exposure potentials
- lower quality of performance than other technologies
- contact time issues
- should not be used on more reactive metals like zinc

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
7.	*Foams and Gels* Carrier agents for chelators and acids to increase contact time and improve removal.		●	●	◒	○
	• foam generating equipment is cheap, simple, and reliable • manual or remote use • applicable to surfaces in any orientation • produces low volumes of waste • little risk of aerosol generation • increased “dwell time” as compared to liquids • can be specific to radionuclides • specialized training not required • surface pretreatment not usually required	• health and safety issues (slippery, label posting required) • waste management issues (must neutralize) • concentrates radionuclides leading to increased exposure potentials • repeated application may be necessary due to less decontamination agent present in foam versus solution • flow characteristics prevent them from being effective (*e.g.*, deep crevices)				
8.	*Oxidizing and Reducing Agents* Controls or modifies the oxidation state of a contaminant to improve its solubility in solution.		○	◒	○	○
	• simple processes have low costs • produces low volumes of waste • little risk of aerosol generation • can be specific to radionuclides	• complex processes can be very expensive • health and safety issues (chemicals) • waste management issues (must neutralize) • concentrates radionuclides leading to increased exposure potentials • may require highly skilled workers • may require significant scientific and engineering support				

SURFACES, PHYSICAL

9. *Removal*

● ○ ◒ ◒

- works on most surfaces
- may be only option on porous materials
- achieves higher decontamination factor than chemical decontamination
- surface preparation not usually an issue
- waste management tends to be simpler (no secondary waste)

- no radionuclide or chemical specificity
- likely to be destructive to the surface
- airborne emissions
- limited access to complex geometries
- more "hands-on" potentially leading to higher worker doses
- waste volumes can be larger
- set-up issues

10. *Strippable Coatings*

Paints or polymers applied to a surface to encase or extract surface contamination for removal.

● ◒ ○ ◒

- produces a single solid waste
- prevents or reduces airborne contaminants
- used to mitigate nonradioactive waste [polychlorinated biphenyls (PCBs), asbestos, and metals)]
- equipment easy to mobilize
- does not require water source to operate
- internal contamination unlikely

- temperature dependent (4 to 32 °C)
- maintenance issues (*e.g.*, clogging spay nozzle)
- respiratory protection likely needed only during application
- applicable to easily removed contaminants

11. *Centrifugal Shot Blasting*

Hardened steel shot fractures the surface and removes surface contaminants

● ◒ ○ ○

- usually results in a relatively smooth surface which can be reused
- surface depths up to 12.7 to 25.4 mm deep
- ideal for 1.6 to 3.2 mm depths

- maintenance issues (*e.g.*, HEPA filters, vacuum)
- respiratory protection likely needed during application
- units can be limited by their large size and weight
- cannot operate near exterior or in narrow areas (use a grinder instead)
- escape shot blast poses significant hazard

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
12.	*Concrete Grinder* Diamond grinding wheel to decontaminate and strip concrete surfaces		◒	◒	○	○
	• usually results in a relatively smooth surface which can be reused • surface depths up to 1.5 to 3 mm deep • quick and easy compared to similar technologies • less dust generated than scabbler and scalar technologies • reduced worker exposures to contaminants and vibration	• smaller sized jobs • respiratory protection likely needed during application • noise • potential dust generation				
13.	*Concrete Shaver* Diamond edge drum physically removes the contaminant		○	◒	○	○
	• usually results in a relatively smooth surface which can be reused • surface depths up to 12.7 mm • less dust generated than scabbler technology • reduced worker exposures to contaminants and vibration • cost savings versus scabbler	• limited to large open areas with few obstacles • respiratory protection likely needed during application • potential weight limitations (hundreds of kilograms) • intended for floors				
14.	*Concrete Spaller* An expandable bit is inserted into drilled holes causing the concrete to split for removal		○	◒	○	○
	• fast and efficient decontamination at surface depths >3 mm • can be used to gather concrete samples for analyses • can be used on floors and walls	• leaves uneven surface • limited commercial availability • limited to large open areas with few obstacles • respiratory protection likely needed during application				

15. *Dry Ice Blasting* Accelerated dry ice pellets impact the surface providing a temperature and physical shock to remove the contaminant	• may be used to remove semi-fixed contaminated materials (sludge, dirt) on nonporous materials • can be used on floors, walls, and irregular shaped objects • generates very little waste	• requires superior off-gas treatment systems • slow • air monitoring to ensure safe carbon dioxide levels (threshold limit = 5,000 ppm)	◒	●	○	○
16. *Dry Vacuum Cleaning* HEPA filters used to remove small particles from surface	• ideal for loose contamination • can be used on floors, walls, ceilings, and other irregular shaped objects • minimal waste generation • readily available • works well with other physical decontamination technologies	• not effective against fixed contamination • not appropriate for porous materials due to the tendency to push debris further into matrix	●	●	◒	◒
17. *Electro Hydraulic Scabbling* Short high current electrical discharge in water to create a plasma bubble and shockwave to scabble concrete surfaces	• minimal waste generation • virtually no airborne contamination • minimal water consumption • single pass scabbling • high processing rate • minimal labor requirements	• cannot accommodate complex geometries • not usable on metals, plastics, and wood • requires skilled operation • equipment weight (500 kg) • significant power requirements	○	●	○	○

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
18.	*En-vac® Robotic Wall Scabbler* grit blasting unit combined with high vacuum suction		○	◒	○	○
	• minimal waste generation • minimal airborne contamination due to vacuum operation • single pass scabbling • high processing rate	• costly for obstructed areas and small jobs • not usable on metals, plastics, and wood • requires skilled operation • equipment weight (5,000 kg)				
19.	*Grit Blasting* Abrasive particles are pneumatically accelerated against a surface to remove contaminants.		●	◒	◒	○
	• widely available technology • numerous grit selection for a variety of applications • useful for floors, walls, and irregular shaped items • minimal waste generation if filtration system used • portable to large fixed system capabilities	• potential dust/airborne emissions • not recommended for plastics and wood				
20.	*High-Pressure Water* Flushing water under high pressure to remove contaminants		●	◒	●	◒
	• useful for difficult to access surfaces • decontaminating complex geometric structures • widely available technology • numerous equipment setups for a variety of applications	• wastewater containment and treatment considerations • not usable on wood, or fibrous materials				

21. *Soft Media Blast Cleaning*
Uses the kinetic energy of a soft media to abrade a surface and absorb contaminants

● ◒ ○ ○

- safer for operators compared to other blasting media and chemical stripper systems
- easily transportable
- waste minimization is achieved by recycling the sponge media
- absorbs and removes contaminants
- reduces dust generation
- virtually no liquid waste
- not impacted by complex geometries

- foam media costs are more expensive than sand blasting media
- reasonably large capital investment cost
- noisy operation
- equipment decontamination necessary due to limited hose length
- feeding operation may be sensitive to humidity

22. *Steam Vacuum Cleaning*
Uses kinetic energy and temperature of the fluid to mechanically dislodge contaminants

● ◒ ● ○

- widely available technology
- numerous equipment setups for a variety of applications
- easy to learn and use
- reduced airborne generation

- weight and electricity constraints
- not designed to decontaminate irregularly shaped objects
- hot parts/pieces potentially increase risk of skin burns
- hose equipment may interfere with decontamination
- ergonomically challenging for workers using equipment
- communication among workers challenging due to large distances (up to 100 m)

23. *Piston Scabbler*
Pistons used to scarify concrete surfaces

● ◒ ○ ○

- minimal airborne emission with vacuum
- minimal waste generated
- remote operations relieve workers from vibration, noise, and related hazards
- good maneuverability and ability to turn on its geometric center

- tripping hazards if remotely operated
- potential for flying objects if not properly contained

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
MEDIA						
24. *Capping and* 25. *Land Encapsulation* Containment technology that prevents the spread of contaminants and restricts water infiltration	• prevents direct contact with contaminants • reduces vertical infiltration of water into waste materials • several cap designs have averaged better than 99.9 % efficiency in preventing percolation of precipitation over 4 y period • land encapsulation licensing requirements specify design measures to prevent unacceptable radiation exposures for a least 500 y	• could be difficult to monitor or evaluate its performance • gas emissions may occur unless it is designed to prevent them • inappropriate where water table is high • long-term maintenance may be required to ensure integrity • does not remove contaminants • may have stringent siting criteria	●	NA	●	◒
27. *Cryogenic Barrier* Refrigeration used to freeze soils in large-scale projects to create an ice barrier around a contaminated zone	• this technology has successfully been maintained for 6 y at a site in the United States	• optimum moisture content of 14 to 18 % for implementation; might be difficult to implement in arid climates • refrigeration unit must continue to operate • remote sites might require electrical power and utility installation • heat from high-level radioactive waste could increase electrical power needs and maintenance costs • nearby structures could be damaged by frost heave if precautions are not taken • does not remove or remediate contaminated media	○	○	○	○

28.	*Vertical Barriers* Containment technology installed around a contaminated zone which prevent infiltration of groundwater	• cement-bentonite slurry walls have achieved permeabilities of 1×10^{-7} cm s^{-1} or less	• not practical for slopes of >1 % or where there is near-surface bedrock or buried rubble/debris • grout curtain installation is very difficult in low permeability soils • many chemicals can interfere with solidification agents; compatibility testing of barrier materials with contaminants is required • keying the bottom of the barrier into an underlying aquitard is critical for effective containment. • does not remove or remediate contaminated media	◒	◒	◒	◒
29.	*Cement Solidification / Stabilization* Reduces mobility of the contaminant	• best suited to highly porous, coarse-grained LLRW in permeable matrices • typically results in solidified mass with permeability $\leq 1 \times 10^{-7}$ cm s^{-1}	• contaminants could inhibit cementation; compatibility testing of cementing agents with contaminants is required • addition of cementing agents typically increases volume by 30 to 50 % • not suitable *in situ* if waste masses are thin, discontinuous, and at or near the surface or if a high water table is present • does not remediate contaminated media	◒	○	◒	○
30.	*Chemical Solidification / Stabilization.* Uses chemicals to reduce mobility of contaminant	• better suited to fine-grained soil with small pores • thermosetting polymer solidified masses have shown permeabilities $\leq 1 \times 10^{-6}$ cm s^{-1} • leach indexes (ANSI/ANS, 2008) from testing chemically solidified masses have been at least 100 times less than NRC recommended minimum	• presence of some contaminants could inhibit solidification; compatibility testing of solidifying agents with contaminants is required • not suitable *in situ* if waste masses are thin, discontinuous, and at or near the surface or if a high water table is present • leach indexes (ANSI/ANS, 2008) from testing chemically solidified masses have been at least 100 times less than NRC recommended minimum • does not remediate contaminated media	◒	○	◒	◒

TABLE C.1—(*continued*)

	Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
31. *Dry-Soil Separation*			◒	○	◒	◒
	• used for separation of gamma-ray-emitting radionuclides; can be modified for beta-particle-emitting radionuclides • best suited to sort soil contaminated with no more than two radionuclides with different gamma-ray energies • reductions of >90 % for ^{239}Pu and ^{241}Am, 99 % for ^{137}Cs	• not effective for soils where radionuclide distribution is homogeneous or where radionuclide concentrations are >30 Bq g^{-1} • large rocks and debris must first be separated and/or crushed • thick vegetation and root systems will lower the efficiency of the soil separation • soil residuals will require further treatment and/or disposal				
32. *Solvent / Chemical Extraction* *Ex situ* chemical separation technology that separates contaminant from soils to reduce waste volume			◒	○	◒	◒
	• reduces waste volume • permits cleaned soil to be return to its location. • used with other technologies such as solidification/stabilization	• complexity of operation depends on the contaminants and matrix • may require separate storage or disposal				
33. *Soil Washing* A process in which water, with or without surfactants, mixes with contaminated soil and debris to remove the contaminants			◒	◒	○	○
	• appropriate where radioactive contaminants are closely associated with fine soil particles (size between 0.25 to 2 mm) • most effective when soil consists of <25 % silt and clay and at least 50 % sand and gravel • reductions in contaminated soil mass ranging from 54 to 70 % and reductions in treated soil concentrations of 57 to 99 %	• particle size distribution, contaminant concentrations and solubilities affect efficiency/operability of soil washer • process might not work for humus soil or where cation exchange capacity is high				

34. *Flotation*
A chemical agent combines with the contaminant to separate it from the matrix in water

◒ ◒ ◒ ◒

- most effective at separating soil particles in the size range of 0.01 to 0.1 mm
- testing showed reduced radium concentrations in uranium mill tailings from 11 to 2 Bq g^{-1} bench testing achieved 80 % volume reductions of ^{226}Ra contaminated soil

- effectiveness varies with soil characteristics including particle size distribution, radionuclide distribution, specific gravity, and mineralogical composition
- larger soil particles might have to be ground or removed prior to flotation
- humus soils can be difficult to treat
- has not been fully demonstrated for radioactive contamination

35. *In Situ Vitrification*
Heating the material to an extremely high temperature which cools into a glass; the contaminants are not moved

○ ◒ ○ ○

- volume is reduced 25 to 50 % resulting in subsidence
- vitrified masses have shown radionuclide retention of >99 %
- does not affect activity levels

- *in situ* vitrification is not appropriate for waste with reactive materials, buried tanks or drums, organics >10 % by weight, high levels of volatile metals (mercury, lead, cadmium), or mixed waste with halogenated compounds (results in poor quality glass)
- high moisture/salt content in soil can increase electrical needs/cost
- high amounts of metal can cause short-circuiting.
- voids ~25 m diameter should be collapsed before treatment
- requires off-gas control systems; volatile radionuclides trapped in the off-gas system during the process require further treatment and/or disposal

TABLE C.1—(*continued*)

Strengths	Limitations	Urban Application	Waste Issues	Operational Issues	Cost
36. *Ex Situ Vitrification* Heating the material to an extremely high temperature which cools into a glass; the contaminants are moved to an off-site treatment facility		◒	◒	○	○
• Toxicity Characteristic Leaching Procedure test results of 100 times below regulatory limits • does not affect activity levels • *ex situ* solidification/stabilization is a mature technology	• not appropriate for mixed waste with high levels of volatile metals (mercury, lead, cadmium) or with halogenated compounds (results in poor quality glass) • waste with >25 % moisture content could cause excessive energy consumption • requires off-gas control systems; volatile radionuclides trapped in the off-gas system during the process require further treatment and/or disposal • complex and requires highly trained personnel				
LIQUIDS					
37. *Ion Exchange* Chemical separation process in liquid waste streams		◒	◒	◒	◒
• removal rates for radium and uranium have achieved 65 to 97 % and 65 to 99 %, respectively • removal rates for ^{137}Cs and ^{89}Sr have achieved 95 to 99 %	• most effective when the contaminant is in the ionic form • presence of more than one radioactive contaminant could require more than one exchange resin or treatment process • pretreatment could be necessary for removing solids, removing organics, modifying pH, or removing competing ions • oxidants in waste stream can damage the ion exchange resin • typically used to treat concentrations up to ~500 mg L^{-1}; concentrations over 4,000 mg L^{-1} will rapidly exhaust bed capacity				

38.	*Chemical Precipitation* Converts soluble contaminants to an insoluble form and which then is removed from the liquid			◒	◒	◒	◒
		• studies have demonstrated removal of 80 – 95 % uranium from pond water, depending on pH, reagent, and reagent dosing	• most effective with optimum pH levels with a relatively narrow range • the presence of more than one radioactive contaminant could require more than one treatment process • pretreatment could be necessary for removing solids or modifying pH • waste sludge will require dewatering; precipitation agents could need to be removed				
39.	*Permeable Reactive Barrier* Passive treatment walls that permit groundwater to pass through the contaminated materials without disturbing the contaminants			◒	NA	◒	◒
		• ideal site would have uniform permeability, low levels of dissolved solids, poorly buffered groundwater and a shallow aquitard to key the barrier • reductions of up to 99.9 % for uranium, 99 % for strontium	• installation costs become prohibitive for depths over 25 m • high levels of dissolved oxygen or dissolved minerals could result in clogging and biomass buildup • less desirable in areas with numerous underground utilities or structural obstructions • takes several years or more for implementation • reactive media might need replacement during treatment process				

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[a] ● = suggests that the decontamination technology or management option is *above average* in its overall use for large-scale cleanup scenarios as compared to the other technologies

◒ = suggests the technology is *average*

○ = suggests the technology is *below average* as compare to others

[b] NA = means the technology is not applicable due to the inherent application (capping and land encapsulation accepts waste)

Cost ratings are very general and were based on a large-scale application of the technology, which may make some technologies more amenable to selection especially if they have a high initial capital cost.

A generic assessment of the ecological impact of land restoration and cleanup techniques for various land types and land-use classes in the United States is provided in Table C.2. The areas examined for cleanup ranged from 0.01 to 10 km^2. A ranking of zero to five for each cleanup method was determined based on the following interpretation:

0 = causes no measurable change in the ecosystem

1 = preferred technique because adverse environmental effects on recovery and side effects of treatment are minimal

2 = conditionally acceptable because of significant impact by the treatment and/or the equipment upon the area

3 = acceptable as a "last-resort" cleanup to remove exceptionally hazardous material while incurring maximum acceptable impact

4 = causes unacceptable damage but can be used as an interim cleanup if the injury is erased during the final treatment

5 = not applicable to the land type for which it is proposed

For further perspective, Table C.3 provides remediation technologies by media type and Table C.4 provides remediation technologies by radioelement.

TABLE C.2—*Summary of conclusions about the effects of various cleanup measures on soil, vegetation and animals in various land-use classes and land types (IAEA, 1989a; 1989b).*

Decontamination Options	Land-Use Classes			Land Types					
	Suburban	Agriculture	Coastal/ Intertidal Marshes	Tundra	Mountain, Subalpine	Coniferous Forest	Deciduous Forest	Prairie	Desert
Natural rehabilitation	4	4	4	3	4	4	4	3	4
Chemical stabilization	4	3	3	5	2	2	2	5	2
Clear cutting vegetation	4	3	3	5	2	2	2	5	3
Stumping and grubbing	4	3	3	5	3	3	3	5	4
Scraping and grading (<5 cm)	3	1	3	1	2	2	2	1	4
Shallow plowing (<10 cm)	4	1	5	5	4	4	3	1	4
Deep plowing (10 to 20 cm)	4	1	5	4	4	4	3	1	4
Soil cover (<25 cm)	2	1	2	2	3	3	3	2	4
Soil cover (25 to 100 cm)	4	1	3	4	4	4	4	3	4
Remove plow layer (10 cm)[a]	2	1	3	1	2	1	1	1	4

TABLE C.2—(*continued*)

Decontamination Options	Land-Use Classes		Land Types						
	Suburban	Agriculture	Coastal/ Intertidal Marshes	Tundra	Mountain, Subalpine	Coniferous Forest	Deciduous Forest	Prairie	Desert
Remove shallow root zone (<40 cm)	4	1	3	2	3	2	2	1	4
Remove scraping and grading, mechanically stabilize	1	1	2	1	1	1	1	1	4
Remove plow layer (10 cm), mechanically stabilize	1	2	2	2	3	2	2	1	4
Remove shallow root zone (<40 cm), mechanically stabilize	4	2	3	2	3	3	3	2	4
Remove scraping and grading, chemically stabilize	2	2	4	5	3	3	2	1	4
Remove plow layer (10 cm), chemically stabilize	2	2	4	5	3	3	2	2	4

Remove shallow root zone (<40 cm), chemically stabilize	4	3	4	5	4	4	4	3	4
Barriers to exclude people	3	2	1	1	1	1	1	3	1
Barriers to exclude large and small animals	3	3	3	3	3	3	3	3	1
Mechanical stabilization by hard surface	5	4	—[b]	—[b]	—[b]	4	4	3	4
Application of sewage sludge	—[a]	1	—[b]	—[b]	—[b]	0	0	—[b]	—[b]
High-pressure washing (<3 cm)	—[a]	—[a]	—[b]	—[b]	3	—[b]	—[b]	—[b]	—[b]
Flooding (3 to 30 cm)	—[a]	—[a]	—[b]	—[b]	5	—[b]	—[b]	—[b]	—[b]
Soil amendments added	—[a]	4	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]	—[b]

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[a] Increases the severity of scraping and grading.

[b] Outside the scope of this work.

TABLE C.3—*Remediation technologies by media type.*

Media	Remediation Technologies																			
	Capping	Land Encapsulation	Cryogenic Barriers	Vertical Barriers	Cement Solidification/Stabilization	Chemical Solidification/Stabilization	Solvent/Chemical Extraction	Dry-Soil Separation	Soil Washing	Flotation	*In Situ* Vitrification	*Ex Situ* Vitrification	Phytoremediation	Ion Exchange	Chemical Precipitation	Permeable Reactive Barrier	Membrane Processes	Adsorption	Aeration	Monitored Natural Attenuation
Soil	•	•	•	•	•	•	•	•	•	•	•	•	•							
Sediment	•	•	•	•	•	•	•	•	•	•	•	•	•							
Sludge	•	•	•	•	•	•	•		•	•	•	•	•							
Tailings	•	•	•	•	•	•	•	•	•	•	•	•	•							
Incinerator ash	•	•	•	•	•	•	•			•	•	•	•							
Bulk waste	•	•	•	•	•	•					•	•								
Buried waste	•	•	•	•	•	•					•	•								
Debris	•	•	•	•	•	•					•	•								
Groundwater			•	•									•	•	•	•	•	•	•	•
Surface water													•	•	•		•	•	•	
Wastewater													•	•	•		•	•	•	
Slurries													•		•				•	

TABLE C.4—*Remediation technologies by radioelement.*

Radioelement	Remediation Technologies																			
	Capping	Land Encapsulation	Cryogenic Barriers	Vertical Barriers	Cement Solidification/Stabilization	Chemical Solidification/Stabilization	Solvent/Chemical Extraction	Dry-Soil Separation	Soil Washing	Flotation	*In Situ* Vitrification	*Ex Situ* Vitrification	Phytoremediation	Ion Exchange	Chemical Precipitation	Permeable Reactive Barrier	Membrane Processes	Adsorption	Aeration	Monitored Natural Attenuation
Uranium	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●
Radium	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●		●
Thorium	●	●	●	●	●	●	●	●	●	●	●	●					●			
Plutonium	●	●	●	●	●	●	●	●	●	●	●	●		●			●			
Cesium	●	●	●	●	●	●	●	●	●		●	●	●	●		●	●			●
Radon	●	●	●	●	●	●					●	●						●	●	
Strontium	●	●	●	●	●	●		●	●		●	●	●	●		●	●			●
Cobalt	●	●	●	●	●	●	●	●			●	●	●		●	●	●	●		●
Technetium	●	●	●	●	●	●			●		●	●		●	●	●				
Americium	●	●	●	●	●	●		●			●	●					●			
Tritium	●	●	●	●	●	●							●	●						●

Appendix D

Economic Analysis Tools

D.1 Introduction

This appendix identifies and discusses the applicability of socioeconomic planning techniques and models useful for planning optimized long-term recovery from a radiological or nuclear incident producing wide-area contamination.

D.2 Cost-Benefit Analysis

Cost-benefit analysis is an approach which attempts to quantify all the possible impacts of a policy or project, to monetize those impacts, and to then determine which alternative under consideration maximizes the sum of benefits less costs. When the costs and benefits occur over time, they must be discounted appropriately since dollars spent or obtained in the future have less "value" than those spent or obtained in the present. The technique is meant to replicate what occurs in a free market. Under certain assumptions, the market will maximize the sum of producer surplus (which is the difference between the price received for a product and the cost of producing it) and consumer surplus (which is the difference between what a consumer would be willing to pay and what they have to pay), which can also be considered to be benefits less costs.

In order to conduct a cost-benefit analysis, the following steps are useful (Boardman, 2001):

1. Specify the set of alternatives; this process has been discussed in Section 5.4.2.
2. Determine whose benefits and costs will be estimated; generally, this determination will include all individuals and businesses in the region under consideration.

3. List the impacts and determine how they can be measured; it is important that both direct and indirect impacts are included.
4. Calculate the impacts over the life of the project; various types of models, such as CGE models, contingent valuation surveys, or econometric models can be used to estimate the impacts.
5. Monetize these impacts; this step can be difficult when impacts such as averted deaths are included or when nonmarketed goods are being affected. (However, the environmental economics literature can help on these issues since environmental goods are often nonmarketed.).
6. Determine and apply the appropriate discount rate to the costs and benefits over the life of the project; a lower discount rate puts more weight on incidents in the future, while a high discount rate puts less weight on those incidents.
7. Calculate the net present value of each option by subtracting the discounted costs from the discounted benefits.
8. Perform a sensitivity analysis by varying the assumptions that have been used in the process. For example, use a different discount rate to see how the net present value calculation is affected by the assumption.
9. Make a policy recommendation based on the results.

There are several advantages to using cost-benefit analysis, one of which is that it is already commonly used for decision making in business and government (OMB, 1992). For example, ICRP Publication 37 (ICRP, 1980) discussed the application of a cost-benefit analysis to decision making about radiation protection. Since many of the decisions will focus on the costs and benefits of bringing back various producers, many of the impacts will be easily quantified and monetized as these are marketed goods. Cost-benefit analysis is viewed as a good model to use when it is important to include all possible effects, including side effects, over the life of an alternative.

The disadvantages of cost-benefit analysis include the likelihood of errors in the analysis. There are several sources of these which include errors in omission of impacts, forecasting of future impacts, measurements, and valuations, especially when monetizing nonmarket impacts such as quality of life or the environment (Boardman, 2001). In addition, cost-benefit analysis does not yield information on which group or groups receive the benefits and which bear the costs. This is an equity issue that needs to be considered separately.

In order to implement a cost-benefit analysis, planners need to have specified several alternatives. The process can then be undertaken and the results used to help planners select the optimum alternative.

D.3 Multi-Attribute Utility Theory

Multi-Attribute Utility Theory (MAUT) is a decision-making tool used to determine the best possible alternative according to the decision-maker's preferences. MAUT develops a way to examine the trade-offs and associated risk inherent in a particular decision. This decision is dependent upon many different criteria (attributes) and relies on the crucial assumption that the decision maker is rational (Linkov *et al.*, 2011). The term *rational* refers to the actions of the decision maker, and connotes that the decision maker will choose more over less, have full information available, and keep preferences constant, and decisions will reflect the transitive property. Preferences being transitive is common in the economics literature; it assumes that someone who prefers Option A to B, and Option B to Option C will typically prefer Option A to Option C. Under these assumptions, this model incorporates the preferences of the decision maker into a utility function (*i.e.*, a mapping of the level of satisfaction or happiness that the individual receives from consuming various combinations of goods and services). The goal of the decision maker then is to maximize this utility.

In order to use this decision analysis, there must first be a clear description of the specific attributes that should be taken into account. Next, each attribute should be assigned a specific criteria weight by the decision maker in relation to the overall importance of the particular attribute in reaching the ultimate goal of the decision. The criteria weight is then normalized to lie between zero and one. There are two important considerations when using this MAUT ranking analysis: the size of the attribute's effect and the weight that is placed on a criterion in relation to others (Linkov *et al.*, 2011). In addition to determining the size and the weight of an attribute, the decision maker has to provide a utility ranking between zero and one for each decision criterion (Baker *et al.*, 2001). The quantitative data for each characteristic are then put into the utility function to obtain the utility measure, which is then multiplied by the criteria weight to obtain the weighted utility score. The score for each characteristic is then tallied to obtain the total utility of each option. This process essentially converts several different decision criteria with many different units into one utility score. These utility scores can be easily compared, thereby assisting in making a knowledgeable decision.

This analysis is commonly used when quantitative data are known about each alternative, which allows for a better estimate of the alternative' utility score. This method is helpful when attempting to understand the multiple criteria and alternatives involved in a complex decision. MAUT enables the decision maker to quantitatively model qualitative objectives (such as safety) as well as capture the risk attitudes of the particular stakeholders.

The disadvantage of this decision-making tool is that construction of multi-attribute utility functions is a very involved and lengthy process, especially if the number of stakeholders becomes large. A method known as Simple Multi-Attribute Rating Technique (SMART), helps to streamline the process. It uses simple utility functions on a broader scale to rank alternatives, just as the lengthier process accomplishes. In SMART, each goal is given a weight which is then normalized to lie between zero and one. Each criterion is given a score between one and five which is then normalized to lie between zero and one. The two are then multiplied together and are summed. The option with the highest "utility" score is chosen. This technique has proved successful and has gained the same results as the more complex MAUT analysis (Baker *et al*., 2001).

D.4 Computable General Equilibrium Models

These models are based on the assumption that the various sectors (*e.g*., industry, households, governments) in the model behave in certain ways. They generally assume that households are utility maximizers who choose the combination of goods and services that make them the most happy, and that firms are profit maximizers (or cost minimizers). Other sectors in the models, such as governments, importers or exporters are assumed to behave in some specified way as well. Equations are then developed that describe the supply and demand decisions by the sectors, focusing on how prices affect the decision makers. Prices adjust themselves in the model so that supply is equal to demand in each of the markets included in the model.

These models are based on input-output accounts which relate the flows of the various commodities through the relevant markets. They are augmented by behavioral parameters such as price and income elasticities for consumers, and input elasticities for producers which are obtained from other studies. Elasticities measure how the consumer and producer respond to changes in prices or income and are generally assumed to be stable over time, thus making it sensible to use those estimated elsewhere. The system of equations is then iteratively solved. The models can be used to examine the impact of a shock to the system, such as a sudden increase in the price of oil (which is an important input in many markets). The results of the model will suggest what the impacts of the price change will be on the new equilibrium.

Since they are based on input-output accounts, computable general equilibrium (CGE) models combine the advantages of models that capture the movement of inputs through the broader economy with the advantages of more general econometric models such as behavioral assumptions and the impact of prices (Rose *et al*., 2009). For example, the elasticity parameters can reflect a community's resilience in the face of a disaster. In addition, since the models are based on assumptions about behaviors, and not on time-series data, they are better able to explain (*i.e*., model) the effects of shocks that have not been seen in the past (Dixon and Parmenter, 1996). This makes CGE modeling a strong candidate for modeling the effects of terrorist attacks on an economy.

The weaknesses of CGE models are their reliance on outside sources for the elasticity parameters, the difficulty of using them to forecast, and the underlying data requirements. The latter weakness is due to the need for input-output accounts. However these data can be obtained and updated over time in order to be available after the disaster. The model has also been criticized for its assumptions of profit and utility maximizing (Greenberg *et al*., 2007), although most economists believe that these assumptions are reasonable.

In order to employ CGE models in planning for long-term recovery, planning groups are advised to work with economists to develop a CGE model for their region and to be sure that they have access to, and frequently update the data needed for the model. Planning groups could use the models to "role play" various recovery scenarios and use the results to inform themselves on the outcome of various choices they might make.

There are several papers in the literature which illustrate the use of CGE models to study the impact of terrorist attacks either *ex ante* or *ex post*. Rose *et al*. (2009) examined the impacts of the September 11 attacks on the economy of the New York region and found that the attacks did not substantially impact the economy. The authors suggested that the size of the New York economy as well as the resilience of the people and the market helped to mitigate the impact.

Giesecke *et al*. (2012) used a CGE model to examine the impact of a hypothetical dirty-bomb attack on Los Angeles. They found that "the economic damage wrought by such an event is dominated by the consequences of business interruption in the short run and behavioral effects in the long run." This finding suggests that policy decisions could help reduce the impact of the attack.

D.5 Pros and Cons Analysis

Pros and cons analysis is a common decision-making tool, and is used when a rather simple decision is being made. The decision involved in a pros and cons analysis has few alternatives that involve few discriminating criteria of equal value (Baker *et al.*, 2001). By laying out the options as pros and cons, decision makers can better assess the weight of each criterion and ultimately make a decision.

In order to produce this analysis, one column of pros (advantages) and one column of cons (disadvantages) for a particular decision are created. Such a construction allows the decision maker to evaluate each column and ultimately decide which column is stronger or more beneficial for the decision maker. The column that is stronger has the most influence over the decision maker and will help with the final educated decision.

The strengths of this analysis are that there are not any mathematical implications and the process of decision making is relatively quick and easy. The weakness of this decision-making tool is that it may not be as applicable to assist in making very complex decisions. It may also be more controversial if there are a large number of stakeholders with divergent opinions.

D.6 Kepner-Tregoe Decision Analysis

The Kepner-Tregoe decision analysis is a tool that essentially quantifies the pros and cons analysis. This method of decision making is used frequently in making moderately complex decisions, and can be implemented quickly if the necessary data are readily available (Baker *et al.*, 2001).

The Kepner-Tregoe decision analysis assigns certain criteria as "musts" and "wants." Selecting criteria that fit the musts category assists in narrowing down the alternatives when making the decision. The remaining alternatives that fit the musts category are then further defined by the wants criteria used in this particular analysis (Gould, 1986). These evaluation criteria are weighted on a scale from 1 (being the least important) to 10 (being the most) (Baker *et al.*, 2001). In addition to the criteria weight, there is an alternative score assigned to each criterion. A score of 10 is given to the alternative that comes closest to meeting the objective; all other criteria are scored relative to this alternative. Finally, the total score is calculated by multiplying the criteria weight by the alternative score. Then, all of these scores are added together for a particular alternative. The alternative with the highest score is ultimately the best option in this analysis.

This decision-making tool is preferred because it only requires minimal calculation. However, this also leads to the major drawback of this decision-making tool: the weighted scale of 1 to 10 is very arbitrary and difficult to apply for precise measurement of certain criteria. Also, the nature of this decision-making tool makes choosing the winner of two close scores complicated.

In order to illustrate this decision-making process, Baker *et al*. (2001) outlined a decision process using the Kepner-Tregoe model to decide which replacement car to purchase. The model is illustrated in Table D.1.

D.7 Analytic Hierarchy Process

The analytic hierarchy process assumes that decision makers are better relative decision makers than absolute decision makers (Baker *et al*., 2001). This means that people are better able to decide a relative winner between two criteria than one single winner among multiple criteria. This tool breaks down a particular decision into a hierarchy of criteria so that the decision maker uses pair-wise comparisons. The analytic hierarchy process is used when there are multiple criteria of both quantitative and qualitative nature.

The analytic hierarchy process uses the nine-point scale below (Baker *et al*., 2001) to compare two specific criteria:

1 = equal importance or preference
3 = moderate importance or preference of one over another
5 = strong or essential importance or preference
7 = very strong or demonstrated importance or preference
9 = extreme importance or preference

Decision makers often start this analysis by ranking the criteria from most important to least important. This allows for easier comparison to other criteria in a pair-wise fashion. This analysis develops matrices to assist in the decision process. For example, if Criterion A is very strongly more important than Criterion B, Criterion A would receive a value of 7 while Criterion B would have a value of 1/7 (the reciprocal) compared to Criterion A. The geometric mean[10] of the rankings is then calculated. This is preferred to the arithmetic mean if there are outliers. The normalized weight of each criterion is then calculated. Pair-wise comparisons of the alternatives with respect to each criterion are then carried out, the geometric mean calculated, and the normalized score obtained. The

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[10] Geometric mean is the *n*th root of the product of *n* values.

Table D.1—*Sample Kepner-Tregoe decision table.*

Criteria/Want Objectives	Criteria Weight	Vehicle	Alternative Score	Total Score
Vehicle 1				
Comfort	5	2.19 m rear seat leg and shoulder room, seats 5	6	30
Safety	10	14 stars	5	50
Fuel efficiency	7	21 mpg	9	63
Reliability	9	80	9	81
Cost	10	$26,000	5	50
			Total	274
Vehicle 2				
Comfort	5	2.24 m rear seat leg and shoulder room, seats 6	9	45
Safety	10	17 stars	8	80
Fuel efficiency	7	19 mpg	8	56
Reliability	9	70	7	63
Cost	10	$21,000	8	80
			Total	324

TABLE D.1—(*continued*)

Criteria/Want Objectives	Criteria Weight	Vehicle	Alternative Score	Total Score
Vehicle 3				
Comfort	5	2.03 m rear seat leg and shoulder room, seats 5	4	20
Safety	10	15 stars	6	60
Fuel efficiency	7	22 mpg	10	70
Reliability	9	65	5	45
Cost	10	$17,000	10	100
			Total	295
Vehicle 4				
Comfort	5	2.26 m rear seat leg and shoulder room, seats 6	10	50
Safety	10	19 stars	10	100
Fuel efficiency	7	21 mpg	9	63
Reliability	9	85	10	90
Cost	10	$24,000	6	60
			Total	363

normalized scores for each alternative are added and the alternative with the highest score is chosen.

The analytic hierarchy process is preferable because both quantitative and qualitative criteria can be used. Also, this decision-making process has been proven to provide meaningful results. The drawback of this analysis is that it is not very flexible in the sense that if decision makers decide that new criteria are to be considered, it is difficult to update the process, especially if the matrices are large. However, there is software to help in this situation (Baker *et al*., 2001).

Appendix E

Risk Communication in Late-Phase Recovery from Nuclear and Radiological Incidents: Strategies, Tools and Techniques

E.1 Introduction

Numerous studies have highlighted the importance of effective risk communication to enable people to make informed choices following disasters, including nuclear accidents and radiological terrorist attacks (Becker, 2007; Covello, 2011a). As noted in *Disaster Resilience: A National Imperative* (NA/NRC, 2012), effective risk communication provides people with timely, accurate, clear, objective, consistent and complete risk information. It is the starting point for creating an informed population that is involved, interested, reasonable, thoughtful, solution-oriented, cooperative, and appropriately concerned.

E.2 Differences Between a Nuclear or Radiological Incident and Other Hazards

Effective risk communication is especially critical during the short-, medium-, and long-term early, intermediate and late phases following a nuclear or radiological incident. Research indicates there are fundamental differences in public response to an emergency resulting from a natural or man-made hazard and public response to a radiological incident involving the release of radioactive materials.

Radiological incidents are unique partly because of the intense public fear of radiation. Unlike many other threats, radiation is invisible, silent and odorless. It can only be detected with specialized equipment. It is unfamiliar and not well understood by members of the public. Even common radiological medical procedures often use terms that mask any reference to radiation. The word "nuclear" was even dropped from magnetic resonance imaging, perhaps to allay patient fears.

E.2.1 *Psychological and Sociological Impacts of a Radiological Incident*

Because of fear and misperceptions, many people will have strong feelings of futility, fatalism and hopelessness. Those who survive the initial disaster will fear possible short-, medium-, and long-term negative effects on health, quality of life, infrastructure, resources, social institutions, economic institutions, and political institutions. These feelings will, in turn, severely impact the public desire and ability to process and absorb information. For example, while only about 249 people were found to have some level of ^{137}Cs contamination following a 1987 ruptured source accident in Brazil, over 120,000 people showed up at monitoring stations to be surveyed for contamination.

Other emotions that will likely be expressed in the recovery stages following a nuclear or radiological terrorism incident include:

- anxiety and distress (Where can we turn for help? Will there be anything left for me? What awful and horrible things are ahead? What do we do now?);
- anger (How could such horrible things be happening to us? Why is no one helping? Doesn't anybody care about us anymore? Where are government authorities when we need them? Why are we getting so little information? Why are we being treated so badly? Why are some people getting more than us?);
- misery, depression and empathy (Will things ever be the same? What can you possibly say to those who have lost everything?);
- hurtfulness (Why do the authorities keep ignoring our wishes and demands? What have we done to justify this horror?); and
- guilt (How is it that we survived and are doing well while others are dead or not doing well?).

Three characteristics of a nuclear or radiological incident make the environment for effective risk communication even worse: large uncertainties, unfamiliarity, and dread.

These three characteristics of a nuclear or radiological incident will result in distinctive impacts on how members of the public think, feel and respond to information during recovery. For example, members of the public will profoundly contribute to heightened perceptions of:

- *lack of control* (*e.g.*, unfolding incidents are largely outside of the control of individual persons and communities);
- *involuntariness* (*e.g.*, risks and burdens are being involuntarily imposed);
- *catastrophic potential* (*e.g.*, severe, permanent and irreversible harm and loss; also fear and apprehension associated with what appears to be an unending series of catastrophic and negative incidents); and
- *social stigma* (attached to people who were contaminated, or even potentially contaminated, by radioactive materials):
  - assistance and services to victims may be denied because of the fear of radiation;
  - residents from the affected locality traveling to other localities may be turned away; and
  - agricultural and other products from the locality may be avoided or banned.

  The social stigma attached to persons exposed to radiation may isolate them and substantially affect prospects for successful long-term recovery.

E.2.2 *Community Support and Communication System*

Unlike other types of emergencies, the intense public fear of radiation will likely heighten perceptions that community plans and procedures for recovery will be largely ineffective, if not completely inoperable for an extended period. This situation will be exacerbated if the incident caused damage to communications infrastructures and cut people off from their normal information channels. Under these circumstances, rumors and misinformation will spread through traditional and social media and will likely take hold.

E.2.3 *Messaging in the Aftermath of a Nuclear or Radiological Terrorism Incident*

Unlike other types of emergencies, people generally do not have the background knowledge of radiation they may have with other risks. With radiation, the knowledge base is not only much more limited, but abounds in myths.

In conversations about radiation, people often mention superheroes, supervillains, and mutated cells and beings. These misconceptions can have a significant impact on how receptive people are to information about radiation. They also point to the hurdles communicators need to overcome to get the important protective action messages out.

As part of an overall interagency planning committee on IND response, a communication subcommittee, led by FEMA, drafted a series of 98 questions and answers for use by agencies responding to questions about a nuclear detonation. These questions ranged from "How do I protect myself and my family?" to "What will the impacts be on air travel and other forms of transportation?"

Following up on this work, CDC (2012) tested selected messages from this document, focusing mostly on protective action messages. The CDC effort and other research indicate that when people are asked to evaluate risk communication messages related to a radiological incident, they typically express a preference for:

- *Messages with clear, specific, prioritized instructions and action items regarding what they can do themselves*: Respondents indicated that messages with clear, specific, prioritized instructions and action items gave them a sense of self-efficacy. These messages also gave them concrete things to do, which in turn, gave them greater feelings of control over their life situation.
- *Messages with information, instructions, guidance, and action items on how to detect, measure and assess levels of radiation*: People indicated that the radiation information provided by experts is often very hard to understand and interpret. People were not sure what radiation is. They did not know if it was dust, if it was mud, or if it would show up as something bright and glowing. They wanted to know how to be able to detect, measure and assess their own risk. They also expressed a desire for information that would help them understand the different ways radiation is measured.
- *Messages containing authoritative language*: People expressed a strong desire for authoritative language, such as: "Do this" or "Don't do that." The more specific the instructions and steps, the better, especially when the information is provided in tiers or layers. People expressed a desire for more information at the same time as expressing a desire for short and clear messages.
- *Messages from trusted sources*: People expressed a strong desire to hear from trusted sources. Trusted sources included elected officials, the president, the mayor, the governor, health officials, response workers, the police chief, the fire chief, media personalities, news anchors, scientists, and weathermen/meteorologists.

- *Messages delivered in real time*: People expressed a strong desire for information from authorities in real time, and a corresponding dislike for prerecorded messages. Hearing a live voice reassured people that someone else was out there, that other people were alive and coping.
- *Messages consistent with existing beliefs*: Because radiation is so unfamiliar, people were unsure how to react. When uncertain, they said they were inclined to do that which was most familiar. For example, many people in New York said they might ignore instructions to stay inside because of the incidents of September 11. People were told to stay inside the WTC and they died. On the other hand, people in Houston, who had lived through hurricanes were more comfortable with the message to "stay inside." Note that this consistency with existing beliefs does not include existing beliefs about radiation, which are largely incorrect, but rather about protective actions.
- *Messages assuring the safety of children*: Many parents said that no matter what the instructions were, they would go and get their children.
- *Messages with clear, regular updates*: Many of the messages that were tested ended with instructions to stay tuned as instructions will change. People expressed a dislike for such messages. Hearing that "instructions will change" made people think that their actions would later be found to be wrong. However, people also recognized the need for authorities to express uncertainty when appropriate. People expressed a specific preference for the following statement: "Instructions and information will be updated as needed."
- *Messages with clear terminology*: Terminology used by emergency responders was often very confusing to people. For example, people didn't know who "responders" were. They were not sure if they were fire, police, government officials, or other agencies. They also did not know the meaning of radiological terminology. They were not sure what "contamination" meant or how to recognize it. They did not know what "exposure," "sheltering." and "shelter-in-place" meant. Many people interpreted "sheltering" to mean go to a shelter, such as a Red Cross shelter.
- *Messages that consider the needs of special populations*: People expressed a desire for authorities to be sensitive to the needs of special populations, including non-English speakers. They noted that the words used by authorities to describe radiation and protective actions can have different meanings

and connotations depending on the person's culture or their country of origin.

- *Messages with useful comparisons*: People found risk comparisons helpful, especially for risks that are invisible and unfamiliar, such as radiation. The most effective comparisons were:
  - same risk at different times;
  - regulatory standard (*e.g.*, public health, food safety, drinking water, or worker safety standard);
  - background levels;
  - other sources of the same risk (*e.g.*, dental or chest x rays; flying cross country at a high altitude);
  - risk of doing something versus not doing something;
  - alternative solutions to the same problem; and
  - same risk as experienced in other places.

  The most difficult comparisons to communicate effectively were those that disregarded the risk perception factors people consider important in evaluating risks (*e.g.*, trustworthiness, fairness, benefits, alternatives, control, dread, catastrophic potential, and familiarity). Listed below are examples of comparisons that are unlikely to be effective:
  - activity released as a result of a radiological incident to the natural activity contained in a banana or Brazil nut;
  - risk of cancer from exposure to radiation to the risk of cancer from consuming peanut butter containing natural carcinogens; and
  - radiation released as a result of a radiological incident to the radiation released from the stone at a memorial site, such as the Lincoln Memorial in Washington, D.C.

E.3 Strategies for Overcoming Barriers to Effective Risk Communication in Recovery from a Nuclear or Radiological Incident

The primary objectives of effective risk communication are to build, strengthen or repair trust; educate and inform people about risks; and encourage people to take appropriate actions.

These objectives apply to all four major types of risk communication:

- information and education;
- behavior change and protective action;
- disaster warning and emergency notification; and
- joint problem-solving and conflict resolution.

Risk communication will directly influence incidents in the short-, middle-, and late-phase recovery stages following a nuclear or radiological incident. Poor risk communication can fan emotions, undermine public trust, create stress, and exacerbate the existing crisis. Good risk communication will create resilience, rally support, calm a nervous public, build trust, encourage cooperative behaviors, and potentially help save lives. A spokesperson who communicates poorly may be perceived as incompetent, uncaring or dishonest (Heath and O'Hair, 2010; Leiss and Powell, 1997). A spokesperson who communicates well will be able to reach large numbers of people with clear and credible messages. Well-constructed, practiced, and well-delivered risk communication messages will inform members of the public, reduce misinformation, and provide a valuable foundation for informed decision making.

The principles of risk communication are supported by a large body of behavioral and social science research [*e.g.*, Bennett and Calman (1999), Covello (1992; 2003), Covello and Sandman (2001), Embrey and Parkin (2002), EPA (2007), Fischhoff (1995; 2009), Hance *et al*. (1990), Heath and O'Hair (2010), Lundgren and McKakin (2009), Mileti and Peek (2000), Morgan *et al*. (1992; 2002), NA/NRC (1989), Sandman (1989), Slovic *et al*. (2001), and Stern and Fineberg (1996)]. Over the past 30 y, thousands of articles on risk communication have been published in peer-reviewed scientific journals. Several reviews of the literature have been published by major scientific organizations, such as the National Academy of Sciences in the United States and the Royal Academy of Sciences in the United Kingdom.

Research shows the mental stress caused by exposure to real or perceived risks can significantly reduce a person's ability to process information. Factors that cause the highest levels of worry, anxiety, and mental stress include, but are not limited to, perceptions that the risk:

- is under the control of others, especially those that are not trusted;
- is involuntary;
- is inescapable;
- is of human origin versus natural origin;
- involves a type of risk that is unfamiliar or exotic;
- threatens a form of injury or death that is dreaded;
- is characterized by a great deal of uncertainty; and
- is likely to cause injury or death to children, pregnant women, or other vulnerable populations.

Virtually all the characteristics associated with high levels of worry, anxiety, mental stress, and perceived risk will be conjured up by perceptions of radiation following a nuclear or radiological incident [*e.g.*, Becker (2007), Lindell and Barnes (1986), and Slovic (1996)]. The challenge for radiation risk communicators is to overcome the communication barriers created by such anxiety-provoking factors (Table E.1).

E.3.1 *Seven Cardinal Rules for Effective Risk Communication*

There are seven cardinal rules for effective risk communication (Covello and Allen, 1988). These cardinal rules are the foundation for effective risk communication.

1. *People have the right to have a voice and participate in decisions that affect their lives.*
2. *Plan and tailor risk communication strategies*: Different goals, audiences, and communication channels require different risk communication strategies.
3. *Listen to your audience*: People's perceptions of risk are influenced by factors other than numerical data. People are usually more concerned about psychological factors, such as trust, credibility, control, voluntariness, dread, familiarity, uncertainty, ethics, responsiveness, fairness, caring and compassion, than about the technical details of a risk. To identify public concerns about risk, organizations must be willing to listen carefully to and understand the audience.
4. *Be honest and transparent*: Honesty and transparency are critical for establishing trust and credibility. Trust and credibility are among the most valuable assets of a risk communicator. Once lost, it is extremely difficult to regain.
5. *Coordinate and collaborate with credible sources of information and trusted voices*: Communications about risks are enhanced when accompanied by validation by sources of information perceived to be credible, neutral and independent. Few things hurt credibility more than conflicts and disagreements among information sources.
6. *Plan for media influence*: The media plays a major role in transmitting risk information. It is critical to know what messages the media are delivering and how to deliver risk messages effectively through the media.
7. *Speak clearly and with compassion*: Technical language and jargon are major barriers to effective risk communication. Abstract and unfeeling language often offends and confuses people. Acknowledging emotions, such as fear, anger and helplessness, is typically far more effective.

TABLE E.1—*Factors important in risk perception.*

Factor	Conditions Associated with Increased Public Concern and Higher Risk Perceptions	Conditions Associated with Decreased Public Concern and Lower Risk Perceptions
Catastrophic potential	Fatalities and injuries grouped in time and space	Fatalities and injuries scattered and random
Familiarity	Unfamiliar	Familiar
Understanding	Mechanisms or process not understood	Mechanisms or process understood
Uncertainty	Risks scientifically unknown or uncertain	Risks known to science
Controllability (personal)	Uncontrollable	Controllable
Voluntariness of exposure	Involuntary	Voluntary
Effects on children	Children specifically at risk	Children not specifically at risk
Effects manifestation	Delayed effects	Immediate effects
Effects on future generations	Risk to future generations	No risk to future generations
Victim identity	Identifiable victims	Statistical victims
Dread	Effects dreaded	Effects not dreaded
Trust in institutions	Lack of trust in responsible institutions	Trust in responsible institutions
Media attention	Much media attention	Little media attention

Accident history	Major and sometimes minor accidents	No major or minor accidents
Equity	Inequitable distribution of risks and benefits	Equitable distribution of risks and benefits
Benefits	Unclear benefits	Clear benefits
Reversibility	Effects irreversible	Effects reversible
Origin	Caused by human actions or failures	Caused by acts of nature

E.3.2 *Risk Communication Models*

Effective risk communication is based on several models that describe how information is processed, how perceptions are formed, and how decisions are made. Together, these models provide the intellectual and theoretical foundation for effective risk communication.

E.3.2.1 *Risk Perception Model*. One of the most important paradoxes identified in the risk perception literature is that the risks that harm people are often very different from the risks that concern, worry or upset people (*e.g.*, Covello and Sandman, 2001; Slovic, 1987; 2000). For example, there is virtually no correlation between the ranking of hazards according to statistics on expected annual mortality and the ranking of the same hazards by how upsetting they are to people. There are many risks that make people worried and upset but cause little harm. At the same time, there are many risks that harm many people but do not make people concerned, worried or upset.

This paradox is explained in part by the factors that affect how risks are perceived. Several of the most important are trust, voluntariness, controllability, familiarity, fairness, benefits, dread, and effects on children. These factors, together with actual risk numbers, determine a person's emotional response to risk information. They affect levels of public fear, worry, anxiety, anger and outrage.

Risk perception theory counters the conventional notion that "facts speak for themselves." People commonly accept high risks and, at the same time, become outraged over much less likely risks. For example, individuals may worry about getting sick from exposure to radiation but then not wear a seat belt in their car because they think, "I'll never be in an accident."

E.3.2.2 *Mental Noise Model*. The mental noise model focuses on how people process information under stress. Mental noise is caused by stress and strong emotions (Covello, 2006). When people are stressed and upset, their ability to process information can become severely impaired. In high stress situations, people typically display a substantially-reduced ability to process information. Exposure to risks associated with negative psychological attributes (*e.g.*, risks perceived to be involuntary, not under one's control, low in benefits, unfair, or dreaded) creates large amounts of mental noise.

People under stress typically:

- have difficulty hearing, understanding and remembering information;
- focus most on the first and last things they hear;

- focus more on the negative than the positive;
- process information at several levels below their educational level;
- can attend to no more than three to five messages at a time;
- focus intensely on issues of trust, benefits, fairness and control;
- interpret nonverbal cues negatively; and
- want to know that you care before they care what you know.

E.3.2.3 *Negative Dominance Model*. The negative dominance model describes the processing of negative and positive information in high-concern and emotionally-charged situations (Covello *et al*., 2001; Kahneman and Tversky, 1979; Kahneman *et al*., 1982). In general, the relationship between negative and positive information is asymmetrical, with negative information receiving significantly greater weight.

The negative dominance model is consistent with the concept of "loss aversion," a central theorem of modern psychology. According to the concept of loss aversion, people put greater value on losses (negative outcomes) than on gains (positive outcomes). When people face uncertainty, they do not typically evaluate the information carefully or compute the risks. Instead, they base their risk decisions and judgments on a brief list of emotions, instincts, and mental short cuts. As Joshua Lehrer points out, "These shortcuts aren't a faster way of doing the math; they're a way of skipping the math altogether" (Lehrer, 2009). People assign a much higher weight to the pain of loss than to the pleasure of gain. In human decision making, losses are feared more than gains. Negatives loom larger than positives.

One practical implication of the negative dominance model is it typically takes several positive or solution-oriented messages to counterbalance one negative message. On average, in high-concern or emotionally-charged situations, it takes three or more positive messages to counterbalance a single negative message. Another practical implication of negative dominance theory is that communications that contain negatives (*e.g*., words such as no, not, never, nothing, none, and words with strong negative connotations) tend to receive closer attention, are remembered longer, and have greater impact than messages with positive words. The use of unnecessary negatives in high-concern or emotionally-charged situations can have the unintended effect of drowning out positive or solution-oriented information. Risk communications are typically more effective when they focus on what is being done rather than on what is not being done.

E.3.2.4 *Trust Determination Model*. A central theme in the risk communication literature is the importance of trust in effective risk communications (Covello *et al.*, 2007; Peters *et al.*, 1997). Trust is generally recognized as the single most important factor determining perceptions of risk. Only when trust has been established can other risk communication goals, such as consensus building, resilience, and dialogue, be achieved. Trust is typically built over long periods of time and is easily lost, and once lost, it is difficult to regain.

Because of the importance of trust in effective risk communication, a significant part of the risk communication literature focuses on trust determination. Research indicates that among the most important trust determination factors are:

- listening, caring, empathy and compassion;
- competence, expertise and knowledge; and
- honesty, openness and transparency.

Other factors in trust determination include accountability, perseverance, dedication, commitment, responsiveness, objectivity, fairness and consistency. Trust determinations are often made in <30 s and are often lasting impressions.

Trust is created in part by a proven track record. It can be substantially enhanced by endorsements from trustworthy sources. The most trustworthy individuals and organizations in many health, safety and environmental risk controversies are (in no priority) informed citizen advisory panels, educators, firefighters, safety professionals, doctors, pharmacists, meteorologists, nurses, and faith leaders.

E.3.3 *Challenges to Effective Risk Communication in the Late-Phase Recovery from a Nuclear or Radiological Incident*

The four models described in Appendix E.3.2 form the backdrop for two of the most important challenges to effective risk communication in the late-phase recovery from a nuclear or radiological incident:

- selectivity and bias in media reporting about risk; and
- psychological, sociological and cultural factors that create public misperceptions and misunderstandings about risks.

E.3.3.1 *Selectivity and Bias in Media Reporting About Risks*. The media play a critical role in the delivery of risk information. However, journalists are often highly selective in their reporting about risks (Hyer and Covello, 2005). For example, they often focus their attention on:

- controversy;
- conflict;
- incidents with high personal drama;
- failures;
- negligence;
- scandals and wrongdoing;
- risks or threats to children; and
- stories about villains, victims and heroes.

Much of this selectively stems from a host of professional and organizational factors, including deadlines, competition, technical expertise, and ratings.

E.3.3.2 *Psychological, Sociological and Cultural Factors that Create Public Misperceptions and Misunderstandings About Risks.* People typically use only a small amount of available information to make risk decisions. Several factors contribute to this, including:

- *Information availability*: The availability of information about an incident (*i.e.*, information is accessible or easily remembered) often leads to overestimation of its frequency. Because of availability, people tend to assign greater probability to incidents of which they are frequently reminded (*e.g.*, in the news media or in discussions with friends or colleagues), or to incidents easy to recall or imagine because of concrete examples or dramatic images.
- *Conformity*: This is the tendency on the part of people to behave in a particular way because everyone else is doing it, or because everyone else believes something.
- *Overconfidence*: Ability to avoid harm is most visible when high levels of perceived personal control lead to reduced feelings of susceptibility. A majority of people, for example, consider themselves less likely than average to get cancer, get fired from their job, or get mugged. Many people fail to use seat belts, for example, because of the unfounded belief that they are better or safer than the average driver. In a similar vein, many teenagers often engage in high-risk behaviors (*e.g.*, drinking and driving, smoking, unprotected sex) because of perceptions of invincibility.
- *Confirmatory bias*: Confirmatory bias is the tendency of people to:
  - seek out and accept information that is consistent with their beliefs or biases;

  - ignore information that is not consistent with their beliefs or biases; and
  - interpret information to support or confirm their beliefs or biases.

  Once a belief about a risk is formed, new evidence is generally made to fit, contrary information is filtered out, ambiguous data is interpreted as confirmation, and consistent information is seen as "proof." Strongly held beliefs about risks, once formed, change very slowly and can be extraordinarily persistent in the face of contrary evidence.
- *Risk aversion*: Risk aversion often translates into a marked preference and demand by members of the public for "statements of fact" over "statements of probability," the language of risk assessment. People often want absolute answers, such as whether food is "safe" or "unsafe." For example, people often demand to know exactly what will happen, not what might happen.

E.3.4 *Strategies for Overcoming Selective and Biased Reporting by the Media About Radiation Risks*

Risk communicators use a variety of strategies to enhance the quality of media reporting. For example, if done in advance, the following strategies can result in better media stories:

- appoint a skilled lead spokesperson with sufficient seniority, expertise, experience, and communication skills to establish credibility with the media and members of the public (note: the leader of an organization is not necessarily the best spokesperson) (Table E.2);
- establish a positive, ongoing relationship with the media (Greenberg *et al.*, 2009); and
- develop a comprehensive risk and crisis communication plan containing the elements found in Table E.3 (CDC, 2002; Covello, 2011b; 2011c).

E.3.5 *Strategies for Overcoming the Psychological, Sociological, and Cultural Factors that Can Create Public Misperceptions and Misunderstandings About Risks*

A broad range of strategies can be used to help overcome distortions in risk information caused by psychological, sociological and cultural factors.

Several of the most important strategies derive from the risk perception model. For example, because risk perception factors such as fairness, familiarity and voluntariness are as relevant as

TABLE E.2—*Desirable communication attributes of a spokesperson following a nuclear or radiological incident*.

- Listen to, acknowledge, and respect the fears, anxieties and uncertainties of members of the public and key stakeholders.
- Remain calm and in control, even in the face of public fear, anxiety and uncertainty.
- Provide people with ways to participate, protect themselves, and gain or regain a sense of personal control.
- Focus on what is known and not known.
- Tell people what follow-up actions will be taken if a question cannot be answered immediately, or tell people where to get additional information.
- Offer authentic statements and actions that communicate compassion, conviction and optimism.
- Be honest, candid, transparent, ethical, frank and open.
- Take ownership of the issue or problem.
- Remember that first impressions are lasting impressions (they matter).
- Avoid humor because it can be interpreted as uncaring or trivializing the issue.
- Be extremely careful in saying anything that could be interpreted as an unqualified absolute ("never" or "always") (it only takes one exception to disprove an absolute).
- Be the first to share bad or good news.
- Balance bad news with three or more positive, constructive, or solution-oriented messages.
- Avoid mixed or inconsistent verbal and nonverbal messages.
- Be visible or readily available.
- Demonstrate media skills (verbal and nonverbal) including avoidance of major traps and pitfalls (*e.g.*, speculating about extreme worst-case scenarios, saying "there are no guarantees," repeating allegations or accusations, or saying "no comment")
- Develop and offer three concise key messages in response to each major concern.
- Continually look for opportunities to repeat the prepared key messages.
- Use clear nontechnical language free of jargon and acronyms.
- Make extensive but appropriate use of visual material, personal and human-interest stories, quotes, analogies, and anecdotes.
- Find out who else is being interviewed and make appropriate adjustments.
- Monitor what is being said on the internet as much as other media.
- Take the first day of an emergency very seriously (drop other obligations).
- Avoid guessing (check and double-check the accuracy of facts).

TABLE E.2—(*continued*)

- Ensure facts offered have gone through a clearance process.
- Plan risk and crisis communications programs well in advance using the anticipate/prepare/practice model (conduct scenario planning, identify important stakeholders, anticipate questions and concerns, train spokespersons, prepare messages, test messages, anticipate follow-up questions, and rehearse responses).
- Provide information on a continuous and frequent basis.
- Ensure partners (internal and external) speak with one voice.
- Have a contingency plan for when partners (internal and external) disagree.
- When possible, use research to help determine responses to messages.
- Plan public meetings carefully (unless they are carefully controlled and skillfully implemented they can backfire and result in increased public outrage and frustration).
- Encourage the use of face-to-face communication methods, including expert availability sessions, workshops, and poster-based information exchanges.
- Be able to cite other credible sources of information.
- Admit when mistakes have been made (be accountable and responsible).
- Avoid attacking the credibility of those with higher perceived credibility.
- Acknowledge uncertainty.
- Seek, engage, and make extensive use of support from credible third parties.

measures of hazard probability and magnitude in judging the acceptability of a risk, efforts to reduce outrage by making a risk fairer, more familiar, and more voluntary are as significant as efforts to reduce the hazard itself. Similarly, efforts to share power (such as establishing a community advisory committee), to be transparent, and to seek support from credible third parties can be as important to making a risk more acceptable as efforts to reduce the hazard itself.

Additional strategies include:

- Using the risk communication templates and tools found in Table E.4, for example:
  27/9/3 Template
  Use when responding to any high stress or emotionally-charged question.
  Recommendation: Be brief and concise in your first response: no more than 27 words, 9 s, and 3 messages.

TABLE E.3—*Twenty-five elements of a comprehensive risk and crisis communication plan for a nuclear or radiological incident.*

- Identify all anticipated scenarios for which risk, crisis and emergency communication plans are needed, including worst cases and low probability, high consequence incidents.
- Describe and designate staff roles and responsibilities for different risk, crisis or emergency scenarios.
- Designate who in the organization is responsible and accountable for leading the crisis or emergency response.
- Designate who is responsible and accountable for implementing various crisis and emergency actions.
- Designate who needs to be consulted during the process.
- Designate who needs to be informed about what is taking place.
- Designate who will be the lead communication spokesperson and backup for different scenarios.
- Identify procedures for information verification, clearance and approval.
- Identify procedures for coordinating with important stakeholders and partners (*e.g.*, with other organizations, emergency responders, law enforcement, elected officials, and provincial and federal government agencies).
- Identify procedures to secure the required human, financial, logistical and physical support and resources (such as people, space, equipment and food) for communication operations during a short, medium and prolonged incident.
- Identify agreements on releasing information and on who releases what, when and how policies and procedures regarding employee contacts from the media.
- Include regularly checked and updated media contact lists (including after-hours news desks).
- Include regularly checked and updated partner contact lists (day and night).
- Identify schedule for exercises and drills for testing the communication plan as part of larger preparedness and response training.
- Identify subject-matter experts (*e.g.*, university professors) willing to collaborate during an emergency, and develop and test contact lists (day and night); know their perspectives in advance.
- Identify target audiences.
- Identify preferred communication channels (*e.g.*, telephone hotlines, radio announcements, news conferences, website updates, and faxes) to communicate with members of the public, key stakeholders and partners.
- Include messages for core, informational and challenge questions.
- Include messages with answers to frequently asked and anticipated questions from key stakeholders including key internal and external audiences.
- Include communication task checklists.

TABLE E.3—(*continued*)

- Include holding statements for different anticipated stages of the crisis.
- Include fact sheets, question-and-answer sheets, talking points, maps, charts, graphics, and other supplementary communication materials.
- Include a signed endorsement of the communication plan from the organization's director.
- Include procedures for posting and updating information on the organization's website.
- Include procedures for evaluating, revising and updating the risk and crisis communication plan on a regular basis.

CCO Template
Use when asked a question with high-emotion.
Steps:
- compassion
- conviction
- optimism

- Developing only a limited number of key messages (ideally three key messages or one key message with three parts) that address the concerns of key stakeholders.
- Developing messages that are clearly understandable by the target audience, typically at or below their average reading grade level, [*e.g.*, see *Plain Language Thesaurus for Health Communications* (CDC, 2007)] and adhering to the "primacy/recency" or "first/last" principle by putting the most important messages in the first and last position in lists:
  - citing credible third parties that support or can corroborate key messages;
  - providing information that indicates genuine empathy, listening, caring and compassion;
  - using graphics, visual aids, analogies, and narratives (such as personal stories); and
  - balancing negative information with positive, constructive, or solution-oriented messages.
- Perhaps most importantly, because of the rapid rate at which information flows through traditional and social media (as quickly as 4 min or less in an emergency or crisis), answers must be prepared, reviewed and cleared in advance to the questions that arise as a result of virtually all disasters (Table E.5) and to the over 400 questions that may arise as a result of a nuclear or radiological incident (Table E.6).

TABLE E.4—*Risk communication templates and tools (use these templates to create effective messages in high concern situations).*

CCO TEMPLATE Use when asked a question with high emotion *Steps:* • **C**ompassion • **C**onviction • **O**ptimism *Example:* (1) "I am very sorry to hear about…; (2) I believe that…; (3) In the future, I believe that …." **"WHAT IF" TEMPLATE** Use when asked a low probability "what if, what might happen" question *Steps:* • Repeat the question (without negatives) • Bridge to "what is" • State what you know factually *Example:* (1) "You've asked me what might happen if….; (2) I believe there is value to talk about what is, what we know now; (3) And what we know is…"	**BRIDGING TEMPLATES** Use when you want to return to your key points or redirect the communication • "And what's most important to know is…" • "However, what is more important to look at is…" • "However, the real issue here is…" • "And what this all means is…" • "And what's most important to remember is …" • "With this in mind, if we look at the bigger picture…" • "With this in mind, if we take a look back…" "If we take a broader perspective, …" • "If we look at the big picture…" • "Let me put all this in perspective by saying…" • "What all this information tells me is…" • "Before we continue, let me take a step back and repeat that…" • "Before we continue, let me emphasize that…" • "This is an important point because…" • "What this all boils down to is…"	**1N = 3P TEMPLATE** **[(One negative equals three positives)/bad news template]** Use when breaking bad news or stating a negative *Recommendation:* Balance one bad news or negative message with a least three or more positive, constructive, or solution-oriented messages **AGL-4 TEMPLATE (average grade level minus four template)** Use when responding to any high stress or emotionally-charged question *Recommendation:* Provide information at four or more grade levels below the average grade level of the audience.

TABLE E.4—(*continued*)

GUARANTEE TEMPLATE
Use when asked to guarantee an incident or outcome

Steps:
- Indicate that the question is about the future
- Indicate that the past and the present help predict the future
- Bridge to known facts, processes or actions

Example: (1) "You've asked me for a guarantee, to promise something about the future; (2) The best way I know to talk about the future is to talk about what we know from the past and the present; (3) And what we know is…" **OR**
"What I can guarantee [assure; promise; tell you] is…"

IDK (I DON'T KNOW) TEMPLATE
Use when you don't know, can't answer, or aren't best source

Steps:
- Repeat the question (without negatives)
- Say "I wish I could answer that"; or "My ability to answer is limited by …;" or "I don't know"
- Say why you can't answer
- Provide a follow up with a deadline
- Bridge to what you can say

Example: (1) "You've asked me about…; (2) I wish I could answer; (3) We're still looking into it; (4) I expect to be able to tell you more by …; (5) What I can tell you is…"

RULE OF 3 TEMPLATE
Use when responding to any high stress or emotionally-charged question

Recommendation: Provide no more than three messages, ideas or points at a time

Example: My three main points are: (1) …; (2)….; and (3)….

27/9/3 TEMPLATE
Use when responding to any high stress or emotionally-charged question

Recommendation: Be brief and concise in your first response: no more than 27 words, 9 s, and 3 messages

PRIMACY/RECENCY TEMPLATE
Use when responding to any high stress or emotionally-charged question

Recommendation: Provide the most important items or points first and last

YES/NO TEMPLATE
Use when asked a yes or no question that cannot be answered yes or no

Steps:
- Indicate you have been asked a yes/no question
- Indicate it would be difficult to answer the question yes or no
- Indicate why it would be difficult to answer the question yes or no
- Respond to the underlying concern

TBC TEMPLATE

Use when responding to questions or concerns indicating high perceived risks or outrage.

Trust message: (*e.g.*, messages communicating listening, caring, honesty, transparency, or competence)
Benefit message: (*e.g.*, messages communicating benefits to the individual, organization or society)
Control message: (*e.g.*, messages that give people things to do or that increase their sense of hope or self-efficacy.

KDD TEMPLATE

Use to give upset people a greater sense of control

Know message: Share what is most important for people to know.
Do message: Share what you are doing to address the concern
Do message: Share what people can do to address the concern

KDG TEMPLATE

Use to give upset people a greater sense of control.

Know message: Share what is most important for people to know.
Do message: Share what is most important for people to do
Go message: Share where people should go for credible information

FALSE ALLEGATION TEMPLATE

Use when responding to a hostile question, false allegation, or criticism

Steps:

- Repeat/paraphrase the question without repeating the negative; repeat instead the opposite; the underlying value or concern, or use more neutral language
- Indicate the issue is important
- Indicate what you have done, are doing, or will do to address the issue

Example: (1) “You’ve raised a serious question about “x”; (2) “x” is important to me; (3) We are doing the following to address “x.”

CARING/SHARING TEMPLATE

Use when responding to a question or statement containing incorrect information.

Caring message: State what you and the person holding incorrect information have in common.
Sharing message (1): Invite the person holding incorrect information to share their information with you
Sharing message (2): Re-share your information

Example: (1)”I assume you asked this question because you care about …., which I also care about; (2) I would greatly appreciate your sharing with me all the information you have so I can review it; (3) In the meantime, the information I have indicates…”

TABLE E.4—(*continued*)

CAP TEMPLATE	**AAF TEMPLATE**	**Acknowledging Uncertainty and Challenges**
Use when responding to a high concern question or statement	Use when the immediate goal is build, maintain, or restore trust	*Sample statements:*
Caring message: Provide a message indicating caring, concern, empathy, or compassion. The message should communicate the seriousness of the situation. **A**ction message: State actions you have, are, or will take to address the issue or problem (*e.g.*, the message might indicate you are cooperating with other organizations or conducting an investigation). **P**erspective message: Provide information that puts the issue in perspective or context.	**A**cknowledge uncertainty and challenges message: Identify knowledge gaps and challenges. **A**ction message: State actions you have, are, or will take to address the issue (*e.g.*, the message might indicate you are cooperating with other organizations or conducting an investigation). **F**ollow-up message: Provide information on where people can obtain timely and credible information.	• "I wish we knew more." • "There are still many uncertainties." • "I had hoped our answers could be more definite by now." • "It must be difficult to hear how uncertain we are." • "There is still much that we do not know…" • "The evidence is still mixed and can be very confusing." • "There are many challenges, unanswered questions, and exceptions." • "There is a range of expert opinion on this issue."

TABLE E.5—*Questions commonly asked by journalists during an emergency or crisis.*

Journalists are likely to ask six questions in a crisis (who, what, where, when, why, how) that relate to three broad topics: (1) what happened, (2) what caused it to happen, and (3) what does it mean. Specific questions include:

- What is your name and title?
- What are you job responsibilities?
- What are your qualifications?
- Can you tell us what happened?
- When did it happen?
- Where did it happen?
- Who was harmed?
- How many people were harmed, injured or killed?
- Are those that were harmed getting help?
- How are those who were harmed getting help?
- What can others do to help?
- Is the situation under control?
- Is there anything good that you can tell us?
- Is there any immediate danger?
- What is being done in response to what happened?
- Who is in charge?
- What can we expect next?
- What are you advising people to do?
- How long will it be before the situation returns to normal?
- What help has been requested or offered from others?
- What responses have you received?
- Can you be specific about the types of harm that occurred?
- What are the names of those that were harmed?
- Can we talk to them?
- How much damage occurred?
- What other damage may have occurred?
- How certain are you about damage?
- How much damage do you expect?
- What are you doing now?
- Who else is involved in the response?
- Why did this happen?
- What was the cause?
- Did you have any forewarning that this might happen?
- Why wasn't this prevented from happening?
- What else can go wrong?
- If you are not sure of the cause, what is your best guess?
- Who caused this to happen?
- Who is to blame?
- Could this have been avoided?

TABLE E.5—(*continued*)

- Do you think those involved handled the situation well enough?
- When did your response to this begin?
- When were you notified that something had happened?
- Who is conducting the investigation?
- What are you going to do after the investigation?
- What have you found out so far?
- Why was more not done to prevent this from happening?
- What is your personal opinion?
- What are you telling your own family?
- Are all those involved in agreement?
- Are people overreacting?
- Which laws are applicable?
- Has anyone broken the law?
- What challenges are you facing?
- Has anyone made mistakes?
- What mistakes have been made?
- Have you told us everything you know?
- What are you not telling us?
- What effects will this have on the people involved?
- What precautionary measures were taken?
- Do you accept responsibility for what happened?
- Has this ever happened before?
- Can this happen elsewhere?
- What is the worst-case scenario?
- What lessons were learned?
- Were those lessons implemented?
- What can be done to prevent this from happening again?
- What would you like to say to those that have been harmed and to their families?
- Is it still dangerous?
- Are people out of danger? Are people safe?
- Will there be inconvenience to employees or to members of the public?
- How much will all this cost?
- Are you able and willing to pay the costs?
- Who else will pay the costs?
- When will we find out more?
- What steps need to be taken to avoid a similar incident?
- Have these steps already been taken? If not, why not?
- What does this all mean?
- Is there anything else you want to tell us?

TABLE E.6—*Questions likely to be asked by members of the public following a nuclear and radiological incident.*

Listed below in categories are over 400 questions members of the public and the media are likely to ask following a nuclear or radiological incident.

Sample health, safety, and mental health questions (general):

- Am I at risk from radiation contamination from the release?
- What are the risks to my children?
- What are the risks to my pets or livestock?
- What will be the impact on natural habitats (*e.g.*, fish, wildlife, and endangered species)?
- Can my children and pets play outside?
- What health effects can I expect to see if I've been exposed to radiation?
- What are the short-term health effects of exposure to radiation?
- What are the long-term effects of exposure to radiation?
- If I develop a health problem (*i.e.*, headaches, rashes) that I never had before, could the exposure to radiation have caused this problem?
- Have any health problems been reported so far?
- How many people have become ill as a result of the release?
- Are you going to test people for exposure to radiation?
- How do you test people for radiation exposure?
- Can people obtain devices for testing radiation exposure?
- Will people in the Emergency Planning Zone be provided with devices for testing radiation exposure?
- Have you set up a temporary, local health center or clinic where we can be tested?
- I'm pregnant (or planning to be). Will exposure to radiation affect my unborn child?
- Will it be safe to garden in my yard?
- Will it be safe to eat vegetables grown in my garden?
- Will it be safe to drink the water and milk?
- Will you provide us with bottled water and milk?
- Is it safe to bathe or shower in the water?
- Is it safe to water our lawns with the potentially-contaminated water?
- Is it safe to mow our lawns if the soil underneath is potentially contaminated?
- Is it safe to use the river for fishing and other recreational purposes?
- Will it be safe to eat the fish caught in rivers and lakes?
- What's being done right now to protect my own health and that of my family?
- How long will the affected area be contaminated?
- How serious is the contamination?

TABLE E.6—(*continued*)

- What health effects are expected from exposures to different types of radiation?
- What health effects are expected to the thyroid glands of those exposed to radiation?
- What health effects are expected to the lungs of those exposed to radiation?
- What health effects are expected for those who ingest food or liquids contaminated with radiation?
- Will the authorities be doing long-term monitoring for increases in thyroid cancer, leukemia, and other cancers among people in affected communities?
- Is there a vaccine people can take to prevent health effects from exposure to radiation?
- Can concrete, walls and glass shield people from the health effects of radiation?
- Are children and pregnant women more susceptible to harm than others from exposure to radiation?
- Are people with weak immune systems more susceptible to harm than others from exposure to radiation?
- What should parents be telling their children?
- What is your advice for people experiencing severe mental anguish or post-traumatic stress syndrome from the incident?
- What should you say to people who [insert risk category, such as people who have lost loved ones, have lost their business, have suffered a financial loss, cannot find families or friends, or witnessed a death or injury]?

Sample questions about potassium iodide (KI):

- Why should people take KI?
- Who should take KI?
- When should people take KI?
- How much protection from radiation is provided by taking KI?
- How effective is KI in protecting against radioactive iodine?
- Do all releases of radioactive material contain radioactive iodine?
- How does KI protect the thyroid gland?
- What is the function of the thyroid gland and what will happen if a person does not take KI?
- Is the taking of KI approved by the U.S. Food and Drug Administration?
- Where can people get KI?
- Does KI require a prescription?
- Are some forms of KI better than others?
- Can people drink the iodine used for the cleaning of wounds if they are not able to get hold of KI?
- Does KI protect against all types of radiation?

- What are the recommended doses of KI for radiological emergencies involving radioactive iodine?
- Who determines what the recommended dosage of KI will be?
- Has the recommended dosage of KI changed over the years?
- Can KI be taken after exposure to radiation has occurred? Is it still effective?
- For how long does the recommended dose of KI provide protection?
- How effective was the KI given to people during the Chernobyl nuclear reactor accident?
- Should people outside the 16 km Emergency Planning Zone take KI?
- Should people outside the 80 km Emergency Planning Zone take KI?
- How far can radioactive iodine travel? What dosages of radioactive iodine are harmful?
- What are the side effects of taking KI?
- Should pregnant women take KI?
- Can KI cause birth defects?
- How quickly does KI work?
- Can one overdose on KI?
- What companies make KI?
- Can you purchase KI on the internet?
- Is enough KI available for all those who might need to take it?
- Are there any groups of people that should not take KI? If so, what are their options?
- Can KI be given to pets?
- Can KI be given to livestock?
- What are the recommended dosages of KI for pets and livestock?
- Should parents consult a pediatrician before administering KI to their children?
- If there is a shortage of KI, should parents give it to their children first?
- Is KI considered to be a medicine?
- If there are side effects from taking KI, who will pay for damages and medical bills?
- How many doses of KI should people take?
- If a person cannot get hold of KI, what are the alternatives? Can table salt help?
- Does the government have enough KI stored for the entire U.S. population?
- Who is in charge of the KI stockpile?
- If there is a shortage of KI, who will get it first? Do you have a priority list of who will get KI?
- Will people living upwind from the nuclear power plant be advised to take KI?
- If people are sheltering in place, how can they get KI?
- Will schools provide KI to students?

TABLE E.6—(*continued*)

- Will people in institutions (*e.g.*, prisons and nursing homes) be given KI?
- Will emergency shelters and reception centers provide KI for evacuees?
- Where can people go to get KI if they are away from home during a radiological emergency?
- What is meant by "65 mg" of KI?
- What is meant by "1 mL" of KI?
- Can you trust websites that sell KI?
- How can you tell if the KI you bought is the real thing?
- If different organizations have different recommendations for KI usage (*e.g.*, about dosage, about when to take it, or about how often to take it), whom should we believe?

Sample radiation / radiological incident questions:
- What is radiation?
- What is the difference between radiation and radioactive material?
- What is the difference between ionizing and nonionizing radiation?
- What are gamma rays?
- Can a person see, feel, taste, smell or hear radiation?
- How much radiation does a nuclear power plant release into the environment as part of its routine everyday operations?
- Do government regulations permit releases of radioactive material into the environment as part of the routine everyday operations of nuclear power plants?
- Are radioactive releases from a nuclear power plant's routine operation fully reported to members of the public and public officials?
- What is a radiation plume?
- What are "radionuclides"?
- How is radiation measured? Why are there so many different types of measurement?
- What is "ionizing radiation"?
- What is "nonionizing radiation"?
- What are "rads"?
- What are "rems" and "millirems"?
- What are "curies," "millisieverts," "microsieverts," and "becquerels?"
- How many [insert radiation measurement term] are in the core of a nuclear power plant reactor and the spent fuel? How much has been released?
- What are "radioactive fission gases"?
- What is meant by "venting" into the atmosphere?
- What is meant by "source term"?
- What is meant by "half-life"?
- What are "radioactive isotopes"?
- What are "noble gases"?

- What is the “half-life” of:
  - radioactive iodine
  - technetium
  - plutonium
  - xenon
  - cesium
  - tritium
  - krypton
  - strontium
- If radioactive material is released, how long will the following elements remain radioactive?
  - radioactive iodine
  - technetium
  - plutonium
  - xenon
  - cesium
  - tritium
  - krypton
  - strontium
- Does exposure to radiation cause:
  - damage to tissue
  - damage to cells
  - damage to DNA (deoxyribonucleic acid)
  - genetic mutations
  - cancers
  - leukemia
  - birth defects
  - reproductive disorders
  - immune system disorders
  - endocrine system disorders
  - other health effects
- Is there such a thing as a “safe dose” of radiation?
- According to government regulations, what are “permissible” levels of releases of radioactive material into the atmosphere and water?
- Does “permissible” mean the same thing as “safe”?
- Is there a difference between the amount of radiation to which a person has been exposed and a radiation dose?
- Who sets radiation protection standards?
- Are radiation protection standards set by all government agencies the same?
- Does the nuclear industry have anything to say in the setting of radiation protection standards?
- Are there different radiation protection standards for workers at NPPs and members of the public?
- Have radiation protection standards for workers and members of the public stayed the same over the years? If they have changed, have they become higher or lower?

TABLE E.6—(*continued*)

- Who's in charge of the emergency response?
- Could this be a terrorist incident?
- Have radionuclides been released into the atmosphere?
- Have radionuclides been released into the water?
- What types of radioactive materials are contained in the radioactive cloud?
- Does the radioactive cloud/vapor/plume contain:
  - iodine
  - technetium
  - plutonium
  - xenon
  - cesium
  - tritium
  - krypton
  - strontium
- Is the NPP monitoring for releases of:
  - iodine
  - technetium
  - plutonium
  - xenon
  - cesium
  - tritium
  - krypton
  - strontium
- Who is tracking the radioactive releases?
- Who is monitoring the radioactive releases?
- If the company that released the radiation is doing the tracking and monitoring, can they be trusted?
- What does the 7-10 rule mean?
- Do you seriously expect us to believe we are exposed to more radiation through bananas, Brazil nuts, and fruits? How stupid do you think we are?

Sample sheltering-in-place questions:

- What is sheltering-in-place?
- How long will people have to shelter-in-place?
- What is the maximum amount of time people will have to shelter-in-place?
- What happens if my ventilation or air circulation system shuts down?
- Can I get radiation sickness from breathing the air in my house even if the windows and doors are shut?
- How effective is it if I close all my windows and doors?
- How effective is it if I shut off the heating of my house or workplace?

- How effective is it if I shut off the cooling system of my house or workplace?
- How effective are face masks?
- How effective are air filters?
- If it is very hot out, should I still turn off the cooling system?
- If it is very cold out, should I still turn off the heating system?
- What is the use of sheltering in place if radiation can penetrate walls?
- If I am in my workplace, should I shelter there or go home?
- Can walls and glass shield a person from exposure to radiation?
- Which types of walls and glass are most effective for shielding from radiation?
- Are there types of radioactive materials that can penetrate walls and glass?
- Are any of the types of radioactive materials that can penetrate walls and glass in the radioactive cloud? If so, why are you recommending sheltering-in-place?
- What should people do if they are not at home when they are advised to shelter?
- What should people do if they are in their car when they are advised to shelter?
- What should people do if they are at the [insert location, such as at the office, restaurant, walking, at a picnic, at a shopping mall, in a government building, or at the movies]?
- If people are away from home, should they try to go home?
- If people live in a trailer or mobile home, should they shelter-in-place?
- Should people stay in their homes after the radioactive plume has passed by?
- What will the environment be like outside when people leave their shelters?
- What should people do before leaving the shelter? For example, should people change their clothes or shower?
- Will it be safe for people to walk to their cars after they exit their shelter?
- What should people take with them when they leave the shelter?
- Will it help if people cover their faces with a handkerchief, towel, or face mask after they leave their shelter?
- Can people touch anything outside after they leave their shelter?
- If a person shelters in a place other than their home, how long will they be gone?Can people be forced to leave their homes or workplace?
- How quickly do people need to find shelter? Is there a maximum amount of time that a person can be outdoors?
- How effective are fallout shelters for sheltering?
- How effective are basements for sheltering?
- Which parts of the home are best for sheltering?
- Are tunnels and underground locations good places to shelter?

TABLE E.6—(*continued*)

- Should people seal windows and external doors that do not fit snugly with duct tape or plastic sheeting to reduce infiltration of radioactive particles?
- If the shelter you are in has only limited amounts of water or food, should you move to another shelter?
- How can people determine if there is radiation in the shelter they have chosen?
- Will trained personnel with specialized equipment be available to detect if radioactive contamination has occurred in the shelter?
- If you don't have a face mask, should you breathe though the cloth of your shirt or coat to limit your exposure?
- If appropriate shelter is not available (such as if you are camping), what should you do?
- How you know when to leave the shelter if you don't have access to a radio, television or telephone?
- Should people take a shower to decontaminate themselves before going inside the shelter if they believe they were exposed to radioactive materials?
- If people believe they were exposed to radioactive materials, should they leave their contaminated clothing outside the shelter?
- What actions should people take when ending shelter-in-place?

Sample evacuation questions:

- How will you notify and warn members of the public (including residential, custodial and transient populations) about ongoing evacuation plans?
- What should people do who do not have a car or other transportation?
- Will it be safe for people to wait at the bus stop?
- How long will people have to wait for a bus?
- How long will people be gone from their homes and businesses?
- What is a "staged evacuation"?
- What is "shadow evacuation"?
- What should I do if an evacuation seems likely?
- What do I do with my livestock?
- What are the boundaries of the evacuation areas?
- Is my neighborhood part of the evacuation area?
- My children are at school and in the evacuation zone. Where will they be taken?
- How can I get in touch with my children who were evacuated from their school?
- My [insert name of relative or friend] is sick and in the hospital that is being evacuated. Where are they moving him/her?
- How can I get in touch with my [insert name of relative or friend] evacuated from [insert location, such as a hospital or nursing home]?

- My house is right on the boundary of the evacuation area. Am I safe?
- What happens if the wind changes directions and blows toward my house? Should I evacuate now?
- If the boundaries of the evacuation zone change, how will people be notified?
- Will people be escorted out of the evacuation zone?
- If I drive my car out of an evacuated area, will the car be contaminated? Will it be confiscated?
- I've been told they are evacuating my neighborhood. What streets should I use to get out safely?
- Is there more than one evacuation route from where I live?
- I've been told to evacuate. Will someone pick me up or am I supposed to drive my own car?
- How will I know I am going the right way? What happens if I get lost?
- Will I have to drive through contaminated areas to get to the shelters?
- Will people be checking to see if I am contaminated before letting me out of the evacuation zone? If so, what will happen to me, my car, and my possessions?
- How will emergency responders know if there is radioactive material (*e.g.*, in my yard, at the school, in the parks)?
- Will the people who are being evacuated on buses be contaminated with radioactive material? How will I know? Will I have to ride with them? If they are contaminated, how will they get the radioactive material off themselves?
- Will there be more than one shelter for each area being evacuated? What will happen if a shelter is full? Will people be sent to another shelter?
- Will they check people for radioactive contamination before letting them into the shelter? If a person is contaminated, what will happen to them?
- If I drive to a location other than a designated shelter, how will the location know if I am contaminated?
- Where do I go to evacuate? I don't have a radio or television.
- Are all evacuation centers the same?
- What is the difference between an "evacuation center" and a "reception center?"
- Do some evacuation centers have better accommodations and amenities than others? Where can I find this information?
- Will evacuation centers have [insert item, such as televisions, radios, telephones, toys for children, rooms for smokers, microwaves, or refrigerators]?
- Will children being evacuated from schools be sent to the same evacuation centers as their parents?
- How long will people have to stay at the evacuation centers?
- I have special medication I need to take. What happens if I run out while I am at the evacuation center?

TABLE E.6—(*continued*)

- I am on a special diet from my doctor due to my health. Will the evacuation center be able to make the food I need?
- I'm on oxygen and have only one canister. Will the evacuation center be able to help me get more?
- My understanding is evacuation centers will not accept pets. Will they make exceptions for small pets (*e.g.*, turtles, rabbits, gerbils and canaries)?
- I don't like being around people I don't know. Will they give me a room by myself?
- Will there be different evacuation centers for VIPs (very important persons)?
- Will the evacuation centers have safes or safety deposit boxes?
- My [insert name of relative or friend] is in [insert custodial facility name, such as a hospital, nursing home] inside the evacuation zone. They are being told to stay put. Are they going to be safe?
- Will I be able to go to the [insert custodial facility name] and pick up [insert name of relative or friend]?
- Will the people who are not able to evacuate die?
- A number of homeless people live under the bridge by the edge of town. Who is going to make sure they get told about the evacuation?
- I know of campers who are in the forest. Who is going to make sure they evacuate?
- Have arrangements been made with adjacent cities, towns and municipalities to shelter folks evacuated from this emergency?
- What facilities have been designated in these adjacent communities as evacuation centers?
- Are the hospitals in the adjacent communities able to take care of people who have been evacuated and are contaminated with radioactive material?
- Who is in charge of ensuring folks get to the right evacuation center?
- Will an attempt be made to get families reunited?
- What happens if the weather or situation changes and the shelters are endangered by the radioactive release? Where will people go then?
- How are you going to get people out of the evacuation zone who are visually or hearing impaired?
- Should I give a ride to people who are hitchhiking or need a ride out of the evacuation zone? Is it safe to give rides to strangers? How will I know if they are contaminated with radioactive material?
- When I leave my home to go to the evacuation center, will my house be safe from vandals and thieves? Will the police stay behind to protect my property?
- What happens if my house catches fire after I have evacuated. Will firemen stay behind to put out fires?

- What happens if I return home and someone has broken into my house? Who will be responsible? Will those who forced me to evacuate be liable?
- I heard they are evacuating my neighborhood. What happens if I refuse to leave my home? Will I be forced to leave? Will they arrest me?
- Do law enforcement officials have the legal right to force me to evacuate?
- If I don't evacuate and get contaminated with radioactive material, will my health insurance pay if I get sick? Who will pay for treatment if a person gets sick from radioactive material?
- Who will pay for property and personal effects that get contaminated following an evacuation?
- Who will pay for a new house if the house cannot be returned to after an evacuation?
- What happens to plants and trees contaminated after an evacuation? Will someone replace them? If so, who will pay for it?
- Who will protect my business if I evacuate?
- Will the National Guard be called in to make sure there is no looting?
- Who will be responsible for property damage or theft at businesses in the evacuation zone?
- Who will pay for losses to businesses closed because of the evacuation?
- What happens if there is a traffic jam? Have you planned for traffic jams?
- Who made the decision to evacuate? Why didn't they evacuate earlier?
- My children go to a school outside the evacuation zone. Who will tell them they cannot go home?
- How much time will people told to evacuate have to pack their things? What should they take with them?
- What are you telling people not affected by this emergency but who are self-evacuating and clogging evacuation routes?
- What are you telling people outside the evacuation zone who nonetheless want to evacuate?
- Are you setting up roadblocks to prevent people from entering the evacuation zone?
- If you evacuate but forgot something at home, will you be allowed back into the evacuation zone?
- Who will stay behind in the evacuation zone? What will happen to them?
- Can personal protective equipment protect those who stay behind in the evacuation zone?
- What are the limits of personal protective equipment?
- Will ambulances be allowed into the evacuated areas?
- What are you telling your own family to do?

TABLE E.6—(*continued*)

- I can stay with [insert name]. Will you provide funds to get me there?
- Will houses and businesses in the evacuation area continue to get electricity and water?

Sample investigation/data questions:

- How far can the radiation spread?
- How bad is the problem?
- How much radioactive contamination is there?
- Is the radiation cloud moving and, if so, how fast and in what direction?
- Are there any other contaminants in the radioactive cloud beside the ones we have been told about?
- How can you be sure there are no other contaminants in the radioactive cloud?
- Will you conduct testing/sampling to make sure the soil in my yard is free of radioactive material?
- How will you decide where to sample and where not to sample?
- Who determines what levels of radiation are considered “safe”?
- Will you cleanup all of the radiation contamination, or will you allow some to remain?
- How will you know whether the drinking water is contaminated?
- How will you know whether my yard has contaminated soil?
- How will you know that it’s safe to breathe the air?
- How will you know whether it’s safe to go fishing?
- Will you sample my well water?
- Why are some people being offered bottled water and not others?
- Can I see the results of all your testing of air, water, soil and buildings?
- Can I see the results of testing you’ve done in areas inside and outside the Emergency Planning Zone?
- Do I have to give you access to sample my property?
- What if I refuse you access to my property?
- Do I need to be home and take time off work while you’re sampling my property?
- I’m moving into the area. Can I see the results of sampling that’s already been done?
- Who will be doing the sampling?
- How can we be sure the sampling data are accurate?
- How can we be sure that future sampling won’t find things that you didn’t find now?
- Can you guarantee the accuracy of the sampling results?

Sample decontamination questions:
- What is decontamination?
- Who will need to be decontaminated?
- Which people will not have to be decontaminated?
- Can people choose not to be decontaminated?
- What will happen to people who choose not to be decontaminated?
- Who will decide who, when, where, why and how people will be decontaminated?
- Who gave authorities the right to make decisions about decontamination?
- Why will people need to be decontaminated?
- How will people be decontaminated?
- Where will people get decontaminated?
- How soon after exposure to radioactive material do people need to be decontaminated?
- Will people have to remove their clothes to be decontaminated?
- Can a person choose not to remove their clothes during decontamination?
- Where will contaminated clothing and personal articles be sent?
- Will people be able to get back decontaminated clothing and personal articles?
- Will there be long lines at decontamination centers?
- Who will do the decontamination?
- Do those who do decontamination have to be certified?
- Will parents be able to stay with their children when they are decontaminated?
- Where will people go after being decontaminated?
- Will people who have been decontaminated be quarantined or isolated from other people?
- Will people be compensated for any clothing or other personal effects that are taken from them for decontamination?

Sample cleanup questions:
- How exactly are you going to cleanup the site?
- Why was this particular cleanup method chosen over other options?
- How long will the cleanup take?
- When are you going to start the cleanup?
- Who is going to perform the cleanup?
- What process was used (or will be used) to select contractors to perform the cleanup?
- How will cleanup performance be monitored or evaluated?
- How much will the cleanup cost?
- Who will pay for the cleanup?
- Will my tax dollars have to pay for the cleanup?
- Can taxpayers be reimbursed for any cleanup costs?
- How will you know when everything is “clean”?
- Will you remove contaminated soil and other radioactive waste?

TABLE E.6—(*continued*)

- Where will you send radioactive waste?
- What if the cleanup doesn't work?
- Can you guarantee that all of the radiation waste and contamination will be removed?
- How will my quality of life be affected during the cleanup (*i.e.*, noise, traffic)?
- After you finish the cleanup, then what? What happens next?
- After the cleanup, will you continue to test to make sure it worked?
- What happens if my water (*e.g.*, or soil) is still contaminated after the cleanup?
- Will people be allowed to return to their homes during the cleanup?
- How long will buildings stay radioactive?
- If the release results in the depositing of cesium, strontium, or other radioactive material, how long will the land stay radioactive?
- Will you continue to do environmental monitoring?
- Will you do health monitoring?

Sample communications questions:
- Why did it take you so long to tell people about the release?
- How can I trust what you're telling me about the release?
- How can I trust what you're telling me about my safety?
- How will I know if my house or property has been contaminated?
- How will I be informed about what's going on?
- Will you share the testing data with residents?
- Will you let us know if something unexpected happens during the cleanup?
- Who should people talk to if they have questions or concerns?
- Where can people get more information about the cause of the emergency?
- Where can people get more information about locations that have experienced similar emergencies?
- If a cleanup plan is selected that residents disagree with, is there an appeal process?
- How will you address public comments?
- Will you address ALL of the public comments?
- How will you decide which comments NOT to address?
- If the majority of residents disagree with how the licensee is planning to cleanup, what can people do to change their plan?

Sample economic questions:
- If my house, property, or business location needs to be abandoned, will I receive financial assistance or compensation?
- If the value of my property or business decreases because of the release, will I be compensated?
- I'm concerned that cost will be the driving force behind the selected cleanup option; does community opinion really matter?

- I was told residents might have to relocate during the cleanup. Who will pay for my moving costs? What about other expenses I may be forced to incur (*i.e.*, costs of transporting my children to school because they won't be able to take the bus, or daily food costs because I won't have access to my stove and refrigerator)
- The release has placed a "negative stigma" on our community that may affect potential investors, developers or homeowners; what are you doing about this?
- Will this emergency keep our community from developing?
- Can we get jobs helping with the cleanup?
- If we can't eat the fish anymore because of health risks, can you give us a food subsidy?
- Do you have enough money to cover the cleanup costs?
- What if you discover the cleanup is going to cost more than estimated, what happens then?

Sample quality of life questions:
- Will martial law be declared?
- Will there be a curfew?
- Will water, telephone, mobile phone, internet, and electricity services be affected?
- Will this incident affect transportation schedules, such as [insert type of transportation, such as airlines, trains, and buses]?
- What steps are being taken to control traffic?
- What steps are being taken to control access to the affected area?
- What steps are you taking to prevent looting from homes or businesses that have been evacuated?
- When will people be able to reschedule community and social events, such as [insert name of event, such as community meetings, concerts, memorial services, and weddings]?
- How will the radiological incident affect mail delivery?
- How, where and when will people get their mail?
- Who will water my plants?
- Who will take care of the pets I had to leave behind?
- Who will take care of the horse I had to leave behind?
- Who will take care of the livestock I had to leave behind?
- Will ATMs be working for those who don't have enough cash with them?
- Will authorities provide cash or coupons to people without cash or credit cards?
- Will the community be stigmatized?

Sample worker safety questions:
- Are workers at risk from radioactive contamination from the release?
- Can workers bring radioactive material on their clothing or hair? What are the risks to their family and children?

TABLE E.6—(*continued*)

- What are the risks to their pets?
- What health effects do you expect to see in workers exposed to radiation?
- What are the short-term health effects of worker exposure to radiation?
- What are the long-term effects of worker exposure to radiation?
- If a worker develops a health problem later, will they be compensated?
- Have any health problems among workers been reported so far?
- How many workers have become ill as a result of the release?
- Are you going to test workers for exposure to radiation?
- Will you monitor the health of workers for decades to come?
- How do you test people for radiation exposure?
- Have you set up a temporary health clinics for workers?
- Will exposure to radiation by workers affect their genes?
- Will it be safe for workers to re-enter the community?
- What health effects do you expect to see in workers?
- Are worker safety standards the same as for members of the public? If not, why not?
- Have worker safety standards changed?
- Do workers receive extra pay for working in radioactive areas?
- What type of personal protective equipment is provided to workers?
- Are workers required to wear personal protective equipment?
- How protective is the personal protective equipment provided to workers?
- Are workers being given KI?
- What should you say to the family of a worker that has lost his or her life?

Sample environmental questions:

- What effects are expected on the community's water supply, including water sheds, reservoirs, and water supply intake and treatment plants?
- What effects are expected on farm crops?
- What effects are expected on domesticated animals?
- What effects are expected on wildlife?
- What effects are expected on livestock?
- What effects are expected on milk and dairy production facilities?
- What effects are expected on the areas people occupy (*i.e.*, where they work, live, play)?
- What effects are expected on soil?
- What effects are expected on food processing plants?
- What effects are expected on endangered species?

E.4 Summary

Listed below is a summary of minimum requirements for effective risk communication in the later phases of recovery from a nuclear or radiological terrorism incident:

- prompt delivery of relevant information to members of the public;
- transparency;
- consistency, clarity and completeness regarding:
  - the use and meaning of radiation measurements (expressed as gray, sievert, becquerel, rad, rem and curie);
  - relevant risk comparisons;
  - how to reduce or avoid exposure to radiation; and
  - risks of radiation exposure to emergency responders and relief workers.
- ensuring that all communication materials are culturally sensitive.

Effective risk communication is central to informed decision making about radiation and radiological emergencies. It is a core practice and competency for all those involved in radiation risk management and health physics. It establishes public confidence in the ability of individuals and organizations to cope with emergencies. The key to successful risk communication is anticipation, preparation, and practice.

Because of institutional and other barriers, strong leadership is often required to implement these strategies. An excellent example of such leadership occurred on September 11, 2001. Mayor Rudolf Giuliani shared the outrage that Americans felt at the terrorist attack on the WTC. He delivered his messages with the perfect mixture of compassion, anger and reassurance (Covello *et al.*, 1986; Davies *et al.*, 1987). For example, when asked about the number of casualties in his first news conference only 4 h after the collapse of the buildings, he said “The number of casualties is greater than any of us can bear ultimately.”

Another important risk communication skill demonstrated by Mayor Giuliani was his ability to communicate uncertainty (Chess *et al.*, 1986). He recognized the challenge to effective risk communication caused by the complexity, incompleteness and uncertainty of risk data. In addressing this challenge, Mayor Giuliani acknowledged uncertainty, explained that risks are often hard to assess and estimate, announced what was known and not known, and announced problems early.

Appendix F

Practical Aspects in the Optimization Process During Late-Phase Recovery

The decision-making process to address late-phase cleanup issues toward recovery will likely be both incident and site specific, and many factors will need to be considered in the optimization approach (Table F.1). While lessons learned from past incidents and exercises (Appendix A) may help address some specific issues, decision makers cannot expect to rely on a uniform recipe with detailed procedures to follow. The general guidance for implementing the optimization approach is discussed in Section 5, and this appendix supplements that guidance with some practical considerations. These considerations are not meant to be all-encompassing or elaborate, but do provide some conceptual and qualitative bases for optimization. This appendix is intended for use both in pre-incident planning exercises and for actual post-incident recovery planning. Nevertheless, considerably more detail and specificity to the incident and the local situations will be necessary to support the actual decision-making process.

This appendix discusses the types of issues likely to be encountered in such an incident, and the type of decision process that would be involved. Definitive endpoints will not be presented; rather the options and possibilities to be considered for a given issue will be discussed. As emphasized throughout this Report, the entire process must engage appropriate stakeholders in the decision making.

F.1 Characterizing Radiological Conditions

Dispersion modeling of radioactive materials (with various levels of sophistication) is used to simulate the progression of an incident.

TABLE F.1—*Factors to be considered in the optimization process for long-term recovery.*

Factors or Attributes	Illustration of Considerations
Areas impacted	Obviously the cost and difficulty of the restoration will be proportional to the size of the impacted area. However, the terrain (*e.g.*, flat lands, mountains, rivers, lakes) will also affect decisions. Similarly, urban, suburban and rural areas all have different needs and problems.
Types of contamination	Although radiological hazards are a primary concern for a radiological or nuclear incident and identity of the radionuclides involved is critical, the chemical and physical forms of the contamination will affect both the risk and difficulties associated with removal or stabilization. These factors are also important to waste management and disposal decisions. In addition, nonradiological hazards (chemical or biological) could also be coincident with the radionuclides and further complicate restoration decisions.
Other hazards	A radiological or nuclear incident can also result in many nonradiological hazards and optimization needs to consider these. They may result from the incident-associated explosions that cause fires, or failures of industrial safety systems that cause release of hazardous materials. There may also be hazards that result from the implementation of the chosen restoration alternatives.
Human health	Human health is a key factor. A primary goal of the alternative selected *via* optimization should be to restore the affected areas so their use will not significantly affect human health.
Public welfare	Public welfare considerations are major factors in restoration decisions. Are there critical land uses that need to be considered? To some degree, one can consider most of the other attributes in this table to be directly or indirectly related to public welfare.
Ecological risks	Ecological risks can result from the incident as a result of widespread contamination of water ways, wet lands, and forests that is sufficiently high to impact ecosystems. However, remedies that result in major alterations of the landscape or waterways may also threaten important ecosystems and must be considered in optimizing the restoration.

TABLE F.1—(*continued*)

Factors or Attributes	Illustration of Considerations
Projected land use	The need for the land and its projected uses is an important factor in optimizing restoration. Levels of cleanup may be less stringent for industrial lands or recreational lands than residential areas. If repopulation or restoration of the lands are not time critical, land use may be restricted (*e.g.*, no farming for some number of years) while short-lived radionuclides decay or weathering reduces the contaminants to insignificant levels.
Historical and cultural resources	Where historical or cultural resources are contaminated, consideration needs to be given to the impact of the remedy on the resources.
Technical feasibility	The ability of technology to provide solutions in a practical and cost effective manner is critical. While simple common actions such as scraping, washing, treating or covering contamination may work in many situations, there are special considerations when decontamination must be done without significantly disturbing contaminated property or a facility. If this cannot be done and use of the property or facility is essential to public welfare, the alternatives selected by the optimization process will need to balance human health and public welfare needs.
Waste disposal options and costs	In general, for small incidents, although waste disposal is important to ensuring effective restoration, disposal alternatives for small amounts of even highly contaminated waste are available and will not significantly impact the optimization decision. However, for larger incidents that are likely to produce large quantities of waste of various types and classes, waste management and disposal options may be limited and costly. Such incidents will likely require new disposal options to be developed and may be a major cost and resource drain.
Costs and available resources	For large incidents, the alternatives available may be limited by the funds and other resources available. The bigger the incident, the more likely that costs will be a limiting factor in the optimization process.

The approach normally considers current and future weather patterns, terrain information, topographic data, and sometimes urban effects. The modeling effort addresses two important issues:

- constructing reasonable plume content, direction, speed, dispersion and deposition; and
- predicting initial radiation doses for emergency response decision making (*e.g.*, evacuation versus shelter-in-place).

The progression of the incident (*i.e.*, from the early phase to the intermediate phase) creates an evolution in information analysis from predictive modeling to monitoring data for contamination from both aerial and ground monitoring.

During the transition from the intermediate phase to the late phase, there is an increasing need to conduct more extensive monitoring in the affected areas to establish "ground truth" and identify the transport of radioactive materials in environmental media air, soil, water and vegetation. Environmental monitoring should always exercise care to account for the potential conditions and factors that may contribute to variation and inconsistency among various measurement methods (Musolino *et al.*, 2012).

In the United States, the radiological environmental monitoring and assessment capabilities are maintained and operated by DOE through the Federal Radiological Monitoring and Assessment Center (FRMAC). The mission of FRMAC is to coordinate and manage all federal radiological environmental monitoring and assessment activities during a nuclear or radiological incident. Among other capabilities, FRMAC coordinates national radiological emergency assets including the Atmospheric Release Advisory Capability, which produces computer models and predictive plots, and the Aerial Measuring System, which provides detection, measurement and tracking of radioactive materials. Collectively, these teams and assets supplement the FRMAC to provide atmospheric transport modeling, radiation monitoring, radiological analysis and data assessments. and tools and services that map the probable spread of radioactive material accidentally or intentionally released into the atmosphere.

Since EPA is the designated lead agency for Emergency Support Function (ESF) #10 (Oil and Hazardous Materials) under the NRF, it also carries the environmental monitoring responsibility, possibly beginning in the very early period of a response and proceeding all the way to late-phase activities. Accordingly, EPA monitors and tracks radiation releases in two ways:

- using monitoring equipment brought to the scene of an incident by its Radiological Emergency Response Team to be used to look for localized areas of radioactive material; and
- using RadNet, the EPA nationwide monitoring system, to monitor the environment on an ongoing basis for larger-scale releases of radioactive material (*i.e.*, large regions of the nation, to global scales).

A conceptual diagram for deploying the modeling and monitoring approaches during phases of the incident is illustrated in Figure F.1. During the Fukushima nuclear accident in March 2011, similar monitoring capabilities were brought to Japan to provide assistance by DOE (Blumenthal *et al.*, 2012; Reed, 2012) and EPA (Tupin *et al.*, 2012). Such capabilities were also illustrated during the Liberty RadEx (LRE) exercise (conducted in 2010 for an RDD scenario at the City of Philadelphia in Pennsylvania) (EPA, 2010; 2011a).

F.2 Environmental Contamination Considerations

F.2.1 *Properties of Contamination in the Environment*

As noted above, initial radioactive plumes are usually predicted by modeling. Once the incident occurs much of the contamination information will come from on-the-ground measurements. Radiological surveillance and monitoring will be relied upon throughout the course of the incident, and perhaps counter-intuitively, even more so when the incident moves into the late phase. Consequently, it is important to understand some of the basic characteristics of radioactive contamination, including the physical and chemical forms of the radionuclides, their environmental distribution and transport, and other factors such as resuspension by both natural and human actions. All of these become increasingly important to decision makers as the incident progresses.

For the most part, contamination will begin as surface deposition and will generally be uniformly distributed, decreasing in concentration with distance from the incident. However, the uniformity of the initial deposition will be affected by weather conditions, terrain, ecosystems, human activities, structures, and so forth. Additional factors such as the particular type of radionuclide, its chemical form, the soil type or media on which the contamination is deposited, and weathering effects (such as rainfall, erosion and resuspension) can change and redistribute the contaminated material over time. The time and rate of change can greatly vary. For incidents involving INDs or nuclear reactors, for example, initial dose and risk potential will decrease quickly due to decay of the short-lived fission products, but beyond six months or so the longer-lived radionuclides begin to

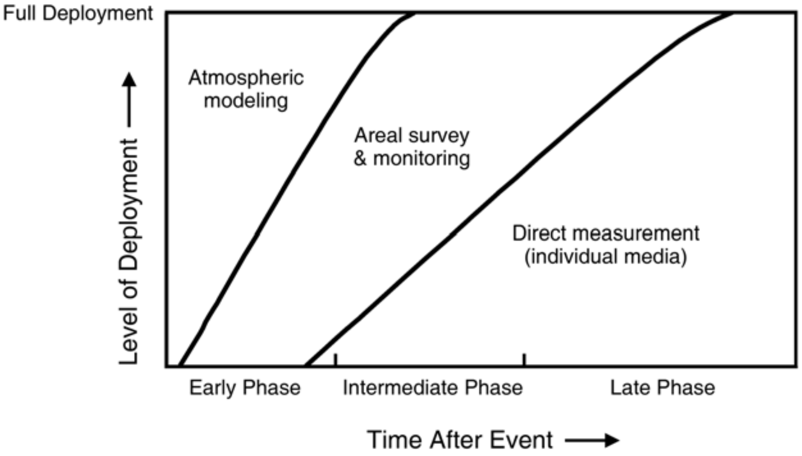

Fig. F.1. Methods for characterizing radiological conditions.

dominate the dose and risk. Thus, radioactive decay, in combination with weathering effects (see the discussion that follows), may constitute a self-mitigating action that will allow relocation recommendations for some areas to be dropped relatively soon (several weeks to a few months) after the incident.

Typical remedial actions at industrial sites, decommissioning of facilities licensed by NRC, or cleanup at DOE research and weapons facilities, deal with contamination that has been in place for many years and is relatively stable. However, the contamination resulting from a nuclear or radiological incident is fresh from the release and can initially be very mobile (and remain mobile for a considerable period of time), and is particularly susceptible to disturbance by wind, rain, and anthropogenic activities (such as foot or vehicular traffic). These factors can cause significant changes to the distribution of contamination within the environment. Several mechanisms that can influence weathering effects are discussed below.

Cesium, a radionuclide typically of concern in an RDD as well as incidents involving INDs or nuclear reactors (due to its abundance in fission products and volatility at high temperatures), is not very mobile in the environment because it usually becomes incorporated in the soils (NCRP, 2006) and can remain near the surface for a considerable time period. However, due to its high solubility in water, its initial deposition is susceptible to erosion and run off, and it has been shown to concentrate in drainage areas, drainspout outfalls and low-lying areas that collect runoff waters. Such areas have been shown to have concentrations up to an order of magnitude greater than other areas (Wallo *et al.*, 1994). Over time, the cesium in these areas binds with the soils and rarely moves more than a few tens of centimeters below the surface unless disturbed by human activities such as gardening or construction. Strontium on the other hand, is relatively mobile and can move down the soil column and into ground waters through percolation. Therefore, although strontium is more likely to threaten water resources, this weathering effect acts to dilute the concentrations and eventually reduces potential risks. Such varied effects tend to complicate both the radiological characterization of the impacted areas and the dose/risk modeling necessary to develop optimized cleanup options. Environmental transport properties of a number of radionuclides commonly used in industry and research, and therefore of concern for use in an RDD are shown in Table F.2.

Other considerations for mitigation include the potential for mixing of the deposited radionuclides into the soil for dilution and using the effects of soil chemistry on uptake by vegetation (including agricultural products). For example, cesium has chemical properties that resemble potassium. It has been shown that application of potassium fertilizer can be used as a counter-measure to reduce ^{137}Cs uptake in plants (Nilsson, 2009).

Table F.3 lists the distribution coefficient (K_d) for various elements for some soil types. The K_d is the ratio of the concentration of an element in soil (*e.g.*, Bq g^{-1}) to the concentration in water (Bq cm^{-3}) in which the soil is immersed, in units of cm^3 (water)/g (soil). It is an important measure of leaching ability for a particular element into the groundwater. The lower the K_d, the more soluble the element is and the more likely it is to be leachable. The last column lists default K_d values compiled for RESRAD (Yu *et al.*, 2001), a computer code used by DOE, NRC, and others to assess doses and risk resulting from residual radioactive materials in soils and to develop cleanup criteria. The defaults are selected to produce conservative estimates of dose and risk and are likely to overestimate actual risk.

F.2.2 *Contamination in Urban/Inhabited Areas*

The migration of radionuclides in urban areas following aerial deposition will depend on the initial physical and chemical form of the contaminants in relation to the materials, orientations and conditions of the surfaces in the environment on which they are deposited, as well as on the weather and various physical and chemical processes (Andersson, 2009). In the urban environment, radionuclides are more likely to move with rainwater into storm sewers and then to either a local surface water body or to the sewage treatment facilities; alternatively, radionuclides may pass with run-off

TABLE F.2—*Environmental transport properties of radionuclides of concern.*

Radionuclide[a,b]	Half-Life/ Decay	Incident	Environmental Factors
Americium-241	432.2 y alpha particle	RDD / IND / reactor	Americium oxide is the most common form in the environment. Americium is typically insoluble, although a small fraction can become soluble through chemical and biological processes. It adheres very strongly to soil; it binds more tightly to loam and clay soils. Americium is a health hazard only if it is taken into the body. Although most americium is excreted soon after ingestion or inhalation, the small fraction that is absorbed is mostly deposited in the liver and skeleton.
Californium-252	2.638 y alpha particle, spontaneous fission	RDD	Californium presents an external hazard due to its high neutron emissions. When taken into the body it is mostly deposited in the bone and can affect blood formation; however, only a small fraction of ingested or inhaled californium actually is absorbed into the blood.
Carbon-14	5,730 y beta particle	IND	Carbon-14 is relatively mobile in the environment and will move downward through the soil column fairly quickly with percolating water to groundwater. Likely to oxidize in high heat. It is only a health hazard if taken into the body. When taken in, it distributes relatively uniformly through all organs.
Cesium-134	2.062 y beta particle/ gamma ray	IND reactor	Cesium is generally insoluble and one of the less mobile metals. Although not generally a concern for drinking water, it can concentrate through the food chain. It represents both an external and internal health hazard. When taken internally, cesium distributes throughout soft tissue, so most is in the muscle. It is cleared from the body in a relatively short period (months).
Cesium-137	30.0 y beta particle/ gamma ray	RDD / IND reactor	

TABLE F.2—(*continued*)

Radionuclide[a,b]	Half-Life/ Decay	Incident	Environmental Factors
Cobalt-60	5.27 y beta particle/ gamma ray	RDD	Cobalt is typically relatively insoluble but certain forms can percolate with the water (*e.g.*, cobalt-cyanide which is usually only present in chemical processing). Forms from INDs and RDDs would not be expected to be very mobile. Cobalt-60 represents a health hazard from both internal and external exposure pathways.
Curium-244	18.11 y alpha particle	RDD	Typical form in the environment is as curium oxide, which is relatively insoluble and adheres to the soil. It presents a health hazard if taken internally (inhalation and ingestion). Most curium inhaled or ingested is cleared before reaching the blood stream and the fraction that remains is mostly deposited in the liver and skeleton.
Iodine-129	1.5×10^7 y beta particle/ gamma ray	IND	Iodine-129 is one of the more mobile radionuclides in soil and can move downward with percolating water to groundwater. It can also concentrate in the food chain. It presents a health hazard only if taken into the body and concentrates in the thyroid.
Iron-55	2.7 y electron capture	IND	Iron is not generally mobile in the environment but can bioaccumulate. Iron-55 emits a weak x ray and does not present a significant external hazard. If taken into the body by ingestion the large intestine is the critical organ and if by inhalation, the spleen and lungs are the critical organs.
Plutonium-238	87.74 y alpha particle	RDD	Plutonium is insoluble and normally remains in the top few centimeters of soil. In aquatic systems it adheres to the sediment. These plutonium isotopes are only a hazard if taken internally. The inhalation hazard is the primary concern because absorption into the body is low following ingestion. Absorbed plutonium deposits mostly in the liver and skeleton.
Plutonium-239	24,065 y alpha particle	RDD / IND reactor	

Radium-226	1,600 y alpha particle	RDD	Radium-226 is present in most soils and rocks. It is found naturally to some degree in groundwater and poses a drinking water hazard. In some soils it can be relatively soluble and in others like clays it will adhere to the particles. Radium-226 presents both an internal and external hazard and its decay products include radon which through its short-lived decay products produces considerable inhalation hazards. Because it is chemically similar to calcium, it is preferentially deposited in the skeleton when taken internally. When radon and its decay products are inhaled the organ at risk is the lung.
Strontium-90	29.12 y beta particle	RDD/IND fission	Strontium is relatively mobile in the environment. Although in a fission incident similar amounts of ^{137}Cs and ^{90}Sr are generated, they separate in the environment as the cesium binds to the surface soil and the ^{90}Sr typically follows the water. The primary hazard from ^{90}Sr is when it is taken into the body. Although the risk and dose coefficient for ^{90}Sr are lower for ingestion than inhalation, ingestion (*e.g.*, drinking water) is the most common exposure mechanism.
Uranium-234	2.45×10^5 y alpha particle	IND reactor	Uranium is naturally present in the environment normally in relatively low concentrations but in some minerals concentrations can be high. Uranium has many potential chemical forms that can significantly affect its solubility and mobility. It is normally one of the more mobile of the radioactive metals. While ^{235}U is a hazard both internally and externally, ^{238}U and ^{234}U are of concern only if taken into the body. However, if uranium is used in an IND, it is likely that the significant component of residual uranium from the incident will be ^{235}U. Uranium taken internally is mostly deposited in the kidney and to a lesser degree in the skeleton.
Uranium-235	7.04×10^8 y alpha particle		
Uranium-238	4.47×10^9 y alpha particle		

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[a] Radionuclides that are likely to be key contributors to long-term dose after an RDD or IND. Most of the radionuclides shown for INDs could also apply to nuclear reactor accidents.

[b] Eleven radionuclides were identified in a study of radioactive material of concern for an RDD incident. Those with half-lives $<1\ y^{-1}$ (^{210}Po and ^{192}Ir) were not included in this table.

TABLE F.3—*Distribution coefficients of elements of RDD and IND interest.*

Element	Geometric Mean K_d (cm^3 g^{-1}) by Soil Type[a]				RESRAD Code Defaults
	Sand	Loam	Clay	Organic	
Carbon	5	20	1	70	0
Cerium	500	8,100	20,000	3,300	1,000
Cesium	280	4,600	1,900	270	1,000
Cobalt	60	1,300	550	1,000	1,000
Iodine	1	5	1	25	0.1
Iron	220	800	165	600	1,000
Plutonium	550	1,200	5,100	1,900	2,000
Polonium	150	400	3,000	7,300	2,000
Radium	500	36,000	9,100	2,400	70
Strontium	15	20	110	150	30
Technetium	0.1	0.1	1	1	0
Thorium	3,200	3,300	5,800	89,000	60,000
Uranium	35	15	1,600	410	50

[a] Geometric means of values from literature.

directly into surface water bodies. Although these pathways will lower the potential for dose and risk in the affected areas, they create new hazards at the treatment facilities or in the surface waters. If a sewage treatment facility is the receptor, the radionuclides can become hazards for the facility workers as the radionuclides may concentrate in the sludge. In addition, the sludge may need to be handled as a radioactive waste, or at least its uses will be restricted. Soluble radionuclides may also be released from the treatment facility back to the surface waters.

In assessing the consequences of airborne releases affecting inhabited areas, it is often estimated that the external dose from the deposited contaminants will be dominated by the contribution from areas of soil. One of the main reasons for this is that the deposited contamination in soil is not removed over time from the surface by wind and weather, as will be the case on many other types of surface in an inhabited environment. For many radionuclides the downward migration in undisturbed soil will be very slow, which implies that the external dose rate may be reduced only slowly through natural processes. Many of the areas of soil in an inhabited area are covered with trees and bushes that are effective in intercepting and retaining the contamination. Whereas the foliage of deciduous trees or bushes will normally be lost in autumn, conifers will retain contaminated foliage over a time span of 2 to 7 y, depending on species. Vegetable gardens may also be found in inhabited areas and the transfer of radionuclides from contaminated soils to edible crops can form a significant component of the annual dose.

However, the production of home-grown foods from urban areas is limited compared with domestic production from rural areas. There is virtually no meat or dairy products produced in urban areas, and fruit and vegetable production is much less than in rural areas [~26 % of city households do some vegetable gardening while 61 % of rural households garden (EPA, 2011)]. Restricting domestic production in urban areas following a contamination incident should be a practicable option for reducing ingestion dose and the cleanup criteria for a given radionuclide could be set at a higher concentration at residences in urban areas than in rural areas while maintaining the same level of protection.

In city areas where people live or work, open, unpaved areas would be small. Other types of contaminated areas (*e.g.*, paved horizontal areas and building surfaces) can give high time-integrated contributions to external dose (Andersson, 2009). Some anthropogenic surfaces in the inhabited environment retain very little of the deposited contamination against wind and weather, whereas other types of surfaces may retain much of the deposited contamination, even after having been exposed to the weather for many years. The inhabited environment exhibits a complexity of surfaces of different material characteristics and orientation, on which deposited contaminants will behave in different ways.

Experimental work carried out after the Chernobyl nuclear reactor accident showed that radiocesium is in general much more strongly retained on roof surfaces than are other contaminants (Roed, 1987). Walls also retain contamination with a weathering half-life of 5 to 10 y, although this is more a reflection of their vertical orientation and inaccessibility to wash-off by rain (Andersson and Roed, 2006). Rainwater running over a contaminated roof to the gutter will carry contamination with it, which over time can result in deep contaminant profiles over small areas of soil around the down pipe. Studies on roads indicate that radiocesium is not well retained on bitumen or asphalt surfaces (Andersson, 2009). Street dust however, resulting from erosion and weathering of urban surfaces, has the potential to bind cesium and other contaminants. The rate of removal from the road surface is then dependent on the volume of traffic. Figure F.2 shows the weathering effects of the cesium radionuclides in various media over time.

NCRP Report No. 129 (NCRP, 1999) discusses resuspension and provides a model that suggests that the resuspension factor decreases by three orders of magnitude over the first year following a deposition incident (initial values of 1×10^{-6} m^{-1} will change to 1×10^{-9} m^{-1} after 1,000 d). Given a nuclear incident and these resuspension factors, the external exposure pathway would be the primary pathway of exposure for the first few years. However, resuspension factors in areas such as along roadways and in high human-activity work areas have been shown to be one or two orders of magnitude greater than in undisturbed areas. Removal of street dust can be enhanced by simple fire-hosing of the street to reduce doses from inhalation of resuspended material. Andersson *et al.* (2002) reported that the cesium concentration on streets decreases rapidly with 70 % of the deposited cesium having a weathering half-life of 120 d and 30 % of the deposited cesium having a weathering half-life of 3 y. Because of the rapid weathering from streets, the cesium concentration on streets is significantly lower than the cesium concentration in soils (Figure F.2). Such a weathering outcome would be expected to hold true for radionuclides with similar chemistry.

On occasions run-off from contaminated roads could go directly into surface waters. This may impact drinking water supplies or recreational uses (*e.g.*, swimming, fishing or boating). Although under most circumstances (except for an IND incident, a severe nuclear accident, or an extremely large RDD), impacts on commercial fishing

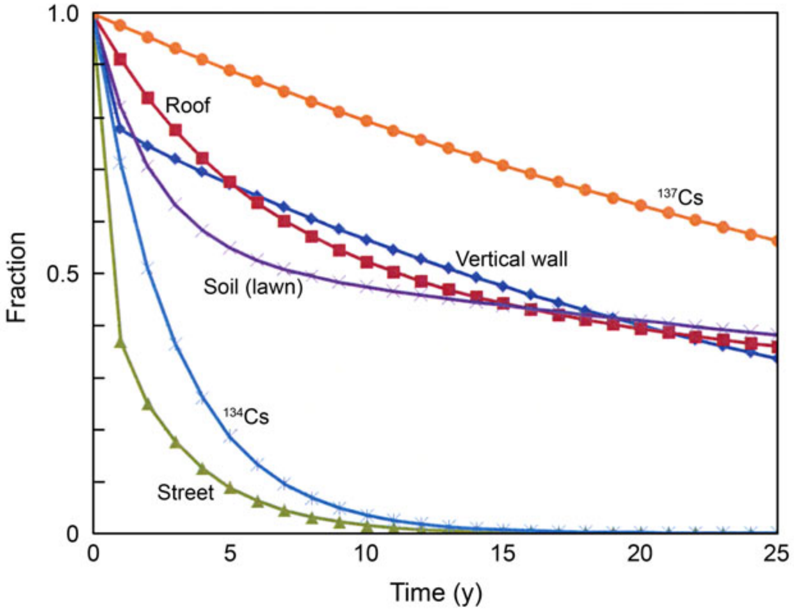


Fig. F.2. Weathering effects of radionuclides on various media (and comparison with natural radioactive decay of ^{134}Cs and ^{137}Cs) (adapted from Andersson *et al*., 2002).

industries would not be likely but would need to be evaluated. These concerns (for an RDD or IND) and pathways were addressed by an interagency Operational Guidelines Task Group and recommendations were issued in the DOE operational guidelines report (Yu *et al*., 2009) to support DHS PAG guidance. Such information may also be expanded to address the potential nuclear species that may result from a nuclear accident.

Reservoirs and rivers or streams used for drinking water supplies can be affected by the runoff from contaminated areas. Dilution of the radionuclides in a large body of water may greatly reduce the risk from ingestion. Similarly, various processes used routinely at water treatment facilities to remove impurities from drinking water will also remove a wide range of radionuclides, reducing some by up to 70 % (Brown and Hammond, 2009). The main processes used are flocculation, filtration and ion exchange and, as at a sewage treatment plant, steps may have to be taken to protect workers from handling contaminated filter media and sludge. Insoluble radionuclides will bind with sediment in the surface water bodies and will not have a significant impact on drinking water supplies. However, much of the aquatic biota lives and scavenges in the sediments and bioaccumulation is possible. This bioaccumulation provides a further route for human exposure through the ingestion pathway.

Areas such as parks, other recreational or historic sites, cemeteries and churches also require special consideration. Due to the low occupancy of these areas (although large numbers of individuals visit these areas, generally people spend only a few hours per week at most) the potential dose and risk for a given concentration of a radionuclide is typically lower than for a residence or industrial location. As a result the optimization process needs to consider the potential for damaging or disfiguring these locations and the associated costs in determining cleanup levels for these infrequently used areas.

In urban areas commercial or industrial facilities may make a significant contribution to the land use. In most cases, largely due to the limited number of exposure pathways (*i.e.*, no ingestion) and lower occupancy factors (people are generally at the work place or shopping centers for less time than they are at home), potential risks to individuals using these areas will be lower for a given concentration of residual contamination. Despite the potential for maximum individual doses to be lower, there may be a potential for a higher collective dose (comprising both workers and visitors) in these situations and hence potentially greater overall risk. Consequently, collective dose/risk needs to be considered in cleanup decisions and the optimization process.

F.2.3 *Risk Characteristics of Residual Contamination*

As noted previously, contamination does not remain static in the environment. As the remediation effort progresses and lands and facilities are brought into service, radiological monitoring will need to continue. Results of regular monitoring should be used to adjust recovery strategies and priorities as needed. Many radionuclides will immobilize after a year or so, although some may remain mobile for decades or beyond, and so raise the concern for potential reconcentration in isolated areas (*i.e.*, forming of "hot spots") that will require special attention. Monitoring plans should be included into the overall late-phase planning and integrated with remediation plans. Monitoring resources should be focused on the higher hazard areas and pathways and those areas where long-term conditions are most uncertain. Other areas should be spot-checked, as resources allow, to verify previous measurements, modeling or assumptions.

An example of particular interest may be surface water bodies where insoluble contaminants have settled in the sediment. Frequent verification that these materials are not causing contamination of water supplies or treatment systems may be warranted.

Periodic sampling of local aquatic biota may be in order to determine if there is bioaccumulation of the radionuclides that could result in increased public health risk or possible damage to local ecosystems. Based on experience from the Chernobyl nuclear reactor accident and early indications from the Fukushima Dai-ichi nuclear accident, it remains unclear whether a major nuclear or radiological incident will create irreversible damage to the ecosystem, and so periodic monitoring may be in order. International and national radiation and environmental protection organizations have developed various tools to support evaluations of potential impacts from radiation on ecosystems (DOE, 2002; 2004; EPA, 1998; ICRP, 2007; 2008; NCRP, 1991). These evaluation processes address radiological risk to both terrestrial and aquatic biota; however, the secondary risk to ecological systems resulting from remedial actions to minimize human health risk are not included, although they could be significant (Whicker *et al.*, 2004). This potential should be evaluated when comparing alternative actions necessary to protect public health.

As mentioned throughout this Report, the DHS (2008a) recommended approach to determining late-phase response is an optimization process for selecting cleanup levels and restoration options. It is a site- and incident-specific process because of the many factors that can influence the viability and practicality of the various options. As part of the effort to develop DHS Planning Guidance, a supporting effort to develop operational guidelines for responding to RDD incidents was conducted through the Operational Guidelines Task Group made up of representatives from federal agencies responsible for responding to RDDs or INDs and supporting DHS in the development of the Planning Guidance. In the report developed through the Operational Guidelines Task Group, benchmark concentrations were presented to illustrate how dose or risk goals and use scenarios might influence cleanup levels that would have to be selected through the optimization process. Effort to expand the operational guidelines further to other nuclear or radiological incidents should follow a similar approach in the future.

As an example, Figure F.3 illustrates the variation in lifetime risk of cancer over time for the 1 mSv y^{-1} effective dose limit for a resident farmer scenario (*i.e.*, a hypothetical resident living off the contaminated land).

NCRP (1999) published screening levels (normalized to an annual effective dose of 0.25 mSv y^{-1}) for contaminated soils that are based on consideration of eight different land-use scenarios including agricultural, suburban and industrial areas. These screening levels may be helpful for planning restoration of a site to the exposure level

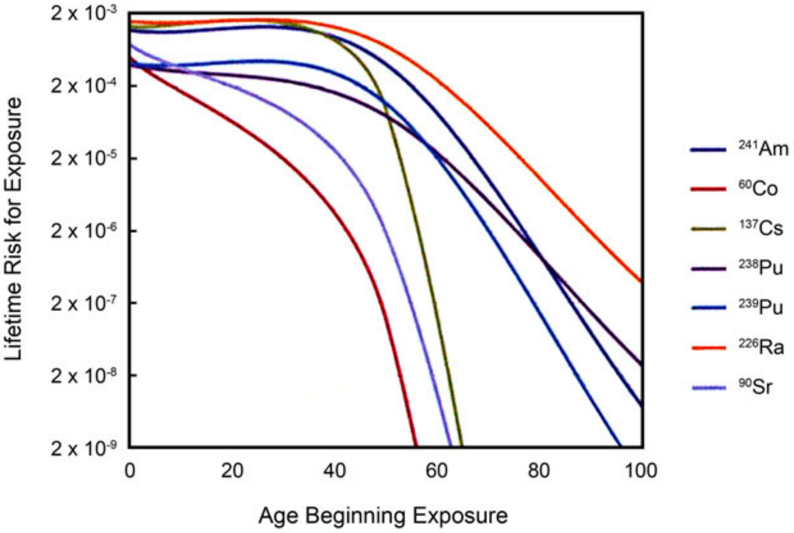


Fig. F.3. Illustration of lifetime risk over time for 1 mSv y^{-1} effective dose maximum dose-based criteria for resident farmer scenario.

selected in final remediation plans. Table F.4 illustrates the difference by radionuclide of the derived concentration level guidelines (or derived cleanup levels based on a predetermined cleanup dose criterion) for specific land-use assumptions. The data indicate that land use and associated restrictions can result in several orders of magnitude difference in the derived cleanup levels. This offers an important consideration for the long-term remediation options for which the key land-use features can be used as bases for achieving dose reduction, as discussed below.

F.3 Remediation Considerations

F.3.1 *Scope of Remediation*

Remediation of an area that has been widely contaminated cannot be dealt with in the same way as the traditional sense of cleanup (Anderson *et al*., 2001; IAEA, 1989b; 1992). For people living in existing exposure situations, as characterized by ICRP (2007), the approach to remediation is to be deliberated through the optimization process, addressing the multiple considerations in decision making. A concerted effort is to be made to bring the initial exposure levels to or below the reference levels in the range of 1 to 20 mSv y^{-1} effective dose, while a typical value used for the long-term post-incident situation is 1 mSv y^{-1} effective dose. The initial focus is on protecting the most highly exposed groups of people

TABLE F.4—*Illustration of variations in derived concentration level guidelines by land-use scenario.*

Radionuclide	NCRP (1999) 0.25 mSv y^{-1} Based Screening Limits in Bq kg^{-1}				
	Agricultural	Sparsely Vegetated Rural	Suburban	Suburban w/o Garden	Commercial Industrial
Americium-241	540	330	1,200	1,900	470
Cobalt-60	79	28	44	45	99
Cesium-137	250	130	200	210	450
Plutonium-238	480	320	1,300	2,400	480
Plutonium-239	490	290	1,200	1,900	470
Radium-226	9	4	5	6	19
Strontium-90	26	14	84	9,300	31,000

from exposures above the reference level (ICRP, 2009). Of course, the objective of the optimization process is to continue bringing about further dose reductions until an optimum balance is reached among exposure level and all other constraints on the situation. Initial remediation can be initiated once the appropriate criteria can be determined upon consultation with stakeholders. As will be discussed later, it may not be feasible to conduct uniform remediation for all contaminated areas. Consequently, carefully thought-out strategies (such as evaluating the various land-use options) with determination of priorities for both immediate and long-term management, are essential to bring about dose reductions over the long term. This complex process is key to optimization in bringing about a systematic remediation approach.

One important factor to consider in the remediation decision is to understand the potential magnitude of the effort to be undertaken by the community (and outside resources) following an incident. Such effort is, of course, related to the size (*i.e.*, area) of the remediation, which is in turn directly correlated with the cleanup criteria (*i.e.*, "How clean is clean enough?"). Such an initial assessment is critical in the decision making, as it helps to provide a tentative scoping of the effort and complexity that might be involved. The effort necessary to remediate contaminated areas is illustrated in Figure F.4, where a conceptual relationship is shown between the size of the contamination area requiring cleanup and the cleanup criteria. Such a relationship is typical of the remediation considerations encountered in past incidents, namely determining how a strict remediation requirement will impact the overall effort. For example, from the Fukushima Dai-ichi nuclear accident of 2011, the contaminated area was estimated to be 1,800 km^2 at a criterion of 5 mSv annual effective dose in the most contaminated areas of the Fukushima prefecture, and increasing to 13,000 km^2 (or approximately the size of the State of Connecticut) at a criterion of 1 mSv annual effective dose across the eight affected prefectures. The stricter decontamination effort in Fukushima prefecture [reducing the criterion from 5 to 1 mSv annual effective dose] was estimated to generate radioactive waste in the form of ~ 29×10^6 m^3 of surface soil and fallen leaves. The decontamination effort would cost about $15.6 billion (IAEA, 2011b; Ishizuka and Harufumi, 2011).

The steep slope of the cost of reducing the exposure criterion requires that planners, stakeholders, and decision makers consider a number of issues in formulating the remediation strategy:

- *Feasibility of remediation*: Some contaminated areas such as forests may not be amenable to decontamination, and so setting predetermined remediation criteria would not be

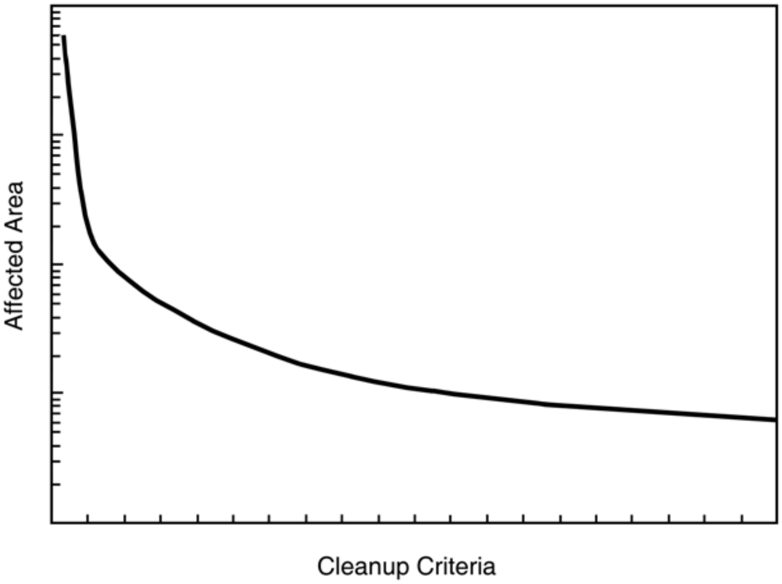


Fig. F.4. Conceptual relationship between cleanup area and cleanup criteria (note: all scales are relative).

practical or feasible. Areas such as streets or open areas could be more readily decontaminated to meet achievable remediation objectives (Section 5.2.2).

- *Remediation options*: An array of remediation options needs to be developed. A wide range of options offers considerable flexibility for remediation under the site- and incident-specific constraints that are not encountered in normal situations. Such options may range from no decontamination, to on-site stabilization, to limited decontamination, to active decontamination (Section 5.4.2). These options can also be exercised in combination with management approaches such as access control, restricting pathways, and other measures to reduce population exposures.
- *Priority for selecting the remediation option*: The primary objective of optimization is to ensure dose reduction adheres to the ALARA principle, and this remains a priority in considering remediation options. However, in doing so, some major constraints such as feasibility of decontamination technology, availability of resources, timing of remediation, waste generation, and stakeholder acceptance, should be factored into the application of the ALARA principle (Section 5.6.2).

Some important considerations for adhering to the ALARA principle are discussed below, including land use, decontamination approaches, and waste issues that are crucial in remediation decisions. The overall dose reduction through long-term management is discussed in Appendix F.4 below.

F.3.2 *Land Uses*

Future land-use options represent an important consideration in developing a feasible remediation strategy. Considerable experiences have been gained from statutory cleanup efforts in the past few decades, with regulatory guidance on land use well established (EPA, 1993; 2001; NRC, 2005; Woolford, 2010). In general, the goal is to identify future land uses that are "reasonably foreseeable (or anticipated)" such that any assessment and future plan associated with the site is reasonable and practical. To accomplish this goal, early engagement and support from the stakeholders of the property's reuse in the recovery effort is essential. Several key elements of land-use considerations are discussed below.

- *Realistic land-use assumptions*: For a community devastated by a major incident, existing land uses should receive priority consideration for repatriating populations displaced during the incident, as well as restoring a certain level of normality to the disrupted community. If returning the site to its original land use is deemed impossible or impractical, then alternate land-use options should be considered. Land-use scenarios should be based on reasonably foreseeable possible land uses at a remedial site (NRC, 2005; Woolford, 2010). The selection process should engage local land-use planning authorities, local officials, and the affected communities' stakeholders, and should take place at the very early stage of recovery. All relevant sources of information should be evaluated, including the community itself, population surveys, topographic and housing data, census projections, and other related sources. Land-use options will be constrained by the level of contamination and options (if any) for remediation. In sparsely populated areas such as forests, for example, the only feasible land use may be a limited remediation effort and restrictions on access to the area.
- *Land-use assessment and future plans*: Assessment of the level of radioactive contamination should be conducted relative to the remediation objectives of the recovery. Specific plans developed by land owner(s), local governments, state, or other stakeholders may identify specific end uses (*e.g.*,

office complex, shopping center, residential areas, agricultural lands). For a wide-area contamination situation, multiple assessments and plans may be needed to address the specific issues for the contaminated areas of interest and the interrelationships among them. There are also short- and long-term issues that need to be considered. For example, some vacant lots may be used temporarily as staging areas for short-term storage of radioactive waste, but their long-term uses should be part of land-use planning. Also, planning for building occupancy will be different from planning for use of the land for agricultural purposes; more information will be needed as the future use of the land becomes more certain.

- *Community involvement*: Successful community involvement involves the principles of engaging stakeholders discussed in Section 5 and also Appendix E.5.3. Because the recovery effort is necessarily community based, decision making on future land uses needs to involve local community leaders, businesses, and residents to gauge their knowledge and interest about the use of sites. Such information will provide important input for future land-use options. The objective of community involvement is to bring about agreement among local residents and land-use planning organizations, together with owners and developers in order to reach some certainty about the future use of the site(s).
- *Developing remediation action objectives*: The remedial action objectives should generally reflect future land-use options and specifically focus on the most reasonable land use. As discussed earlier, the primary objective of recovery is to return the community to a certain level of normality where the existing land use has priority unless it is proven infeasible. To this end, the remediation strategy and approach should be thoroughly discussed and agreed upon with stakeholders in order to fulfill the objectives of the land use. For example, remediation of a contaminated agricultural area needs to consider the acceptance of the future agricultural products grown on the land; if the produce cannot be marketed, alternate land-use objectives need to be explored and defined.
- *Selection of remedial options and alternatives*: The remedial options should be tailored to suit the objectives of selected or alternate land uses. Remedial options may range from limited remediation, to pathway modification, to rigorous decontamination, depending on the objective of the land use (Figure F.5). In general, control of accessibility applies to

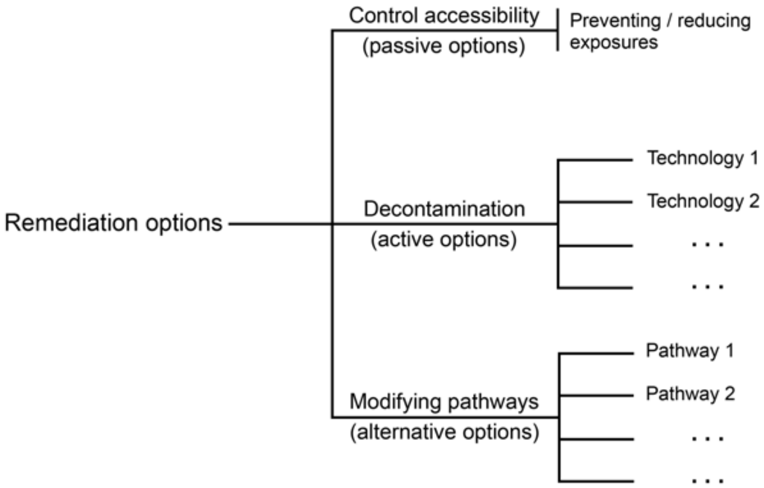


Fig. F.5. Consideration of potential remediation options in late-phase recovery.

low-priority areas (such as forests) for which large-scale decontamination is not feasible. If remedial actions taken on forests are limited, it may be necessary to impose limits on public access or activities (such as hunting or gathering foodstuffs) in order to prevent or reduce exposures to members of the public. Modification of relevant pathways (such as importing foods from uncontaminated areas) will be needed when active decontamination alone will not be able to reduce the exposure levels to the dose criterion. The options are also constrained by the availability and feasibility of specific remediation technologies. Regardless of the options chosen, necessary measures are to be taken to reduce exposure to members of the public. All such actions are to be accompanied by long-term monitoring and management to verify the effectiveness of protective measures.

F.3.3 *Decontamination*

Decontamination is the physical removal of radioactive materials, from contaminated properties. The approach is deployed immediately as a response to an incident. During the early phase, for example, removal of radioactive debris in the impacted area is essential for safe access by first responders and orderly evacuation of affected populations. Decontamination during the intermediate phase helps reduce exposures to workers and members of the public, and so reduces the need for massive relocation efforts. In the late phase, decontamination is focused on further removing the radioactive contamination for recovery (*i.e.*, repatriating the displaced population and accommodating reoccupation of the affected properties).

The cost (and so the efficacy) of a specific decontamination technology for a specific contamination situation is important in decision making for the recovery effort. Figure F.6 shows a conceptual diagram illustrating the potential costs of technology versus the size of the contaminated area. In general, advanced technologies involving active removal of contaminants are highly effective, but may not be cost-effective for deployment in large contaminated areas. Likewise, for a large area contamination, as would be expected from a major nuclear or radiological incident, some low-cost but less efficient technologies (such as natural attenuation) may be favored. The decision to deploy a specific technology for decontamination will be highly dependent on the resource availability and the circumstances of contamination situations. A thorough discussion of existing decontamination technologies has been provided in Appendix C.

One important attribute of a resilient community in the response to a major nuclear or radiological incident is maintaining operation of essential services. Consequently, infrastructures essential to public welfare should receive priority for remediation actions. For the urban community to continue to function, mass-transit services, utilities (power, water, and waste disposal operations), and health services (hospitals and clinics) need to be available. The effort to decontaminate these complex facilities needs to be weighed against the availability of the technology, feasibility of decontamination, allowable residual contamination levels, and potential costs incurred.

In an attempt to decontaminate the highly contaminated area surrounding the Fukushima Dai-Ichi NPP following the accident of 2011, an initial remedial program taken by the Japanese government focused on areas covering ~500 km^2 where annual radiation dose levels were >20 mSv effective dose, and ~1,300 km^2 where the annual radiation dose levels were between 5 and 20 mSv effective dose (IAEA, 2011a). The areas were contaminated mostly with ^{134}Cs and ^{137}Cs from fallout. There is a provisional objective in 2 y to reduce the doses to members of the public (such as in residential areas) by 50 % and to children (such as in school yards or parks) by 60 %. The decontamination effort is designed to take full advantage of natural radioactive decay (and likely the weathering effects discussed in Appendix F.2.1) of ^{134}Cs (half-life of 2.06 y) and ^{137}Cs (half-life of 30.17 y). Measurements obtained during the Fukushima Dai-ichi accident revealed large variations in weathering effect; for example, much faster (twofold) weathering effects than anticipated

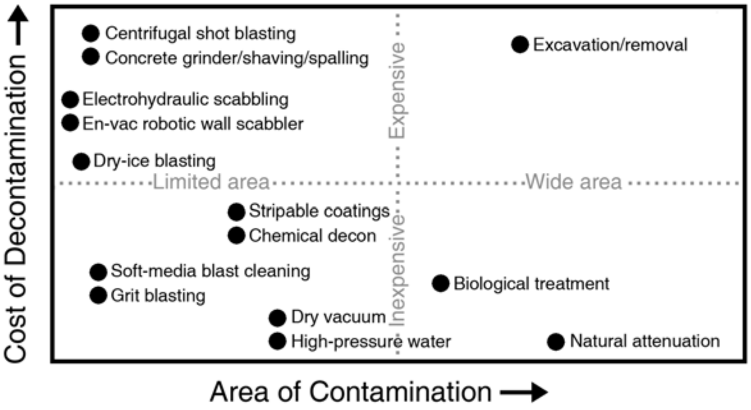


Fig. F.6. Cost implication of decontamination technology over the area of contamination.

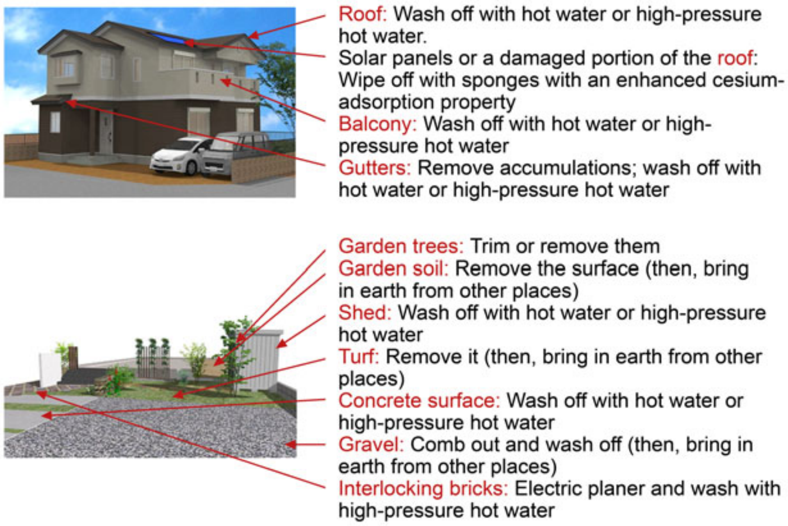
have been observed in urban areas, likely due to precipitation (Musolino *et al.*, 2012).

IAEA has encouraged the Japanese authorities involved in the remediation strategy to cautiously balance the different factors that influence the net benefit of the remediation measures to ensure dose reduction. IAEA suggested that focus should be on doses, not activity concentrations on (or in) various media. The investment of time and effort in removing contamination beyond certain levels from everywhere, such as all forest areas and areas where the additional exposure is relatively low, does not automatically lead to a reduction of doses for members of the public and can generate unnecessarily large amounts of waste.

The range of decontamination approaches implemented in Japan for various land-use options is summarized below.

F.3.3.1 *Decontamination of Housing, Land and Structures*. Some conventional decontamination methods have been applied to housing and structures, as described below and shown in Figure F.7 (Ishida, 2012).

- *Roof*: Wash off with hot water or high-pressure hot water.
- *Solar panels or damaged areas of roof*: Wipe off with sponges with cesium-adsorption property.
- *Balcony*: Wash off with hot water or high-pressure hot water.
- *Gutters*: Remove accumulations (*e.g.*, lichen, fallen leaves, sludge); wash off with hot water or high-pressure hot water.
- *Intricate shapes or where water cannot be used*: Apply peeling agents (*e.g.*, to tiles, walls) by brush and remove when dry.



Roof: Wash off with hot water or high-pressure hot water.
Solar panels or a damaged portion of the roof: Wipe off with sponges with an enhanced cesium-adsorption property
Balcony: Wash off with hot water or high-pressure hot water
Gutters: Remove accumulations; wash off with hot water or high-pressure hot water

Garden trees: Trim or remove them
Garden soil: Remove the surface (then, bring in earth from other places)
Shed: Wash off with hot water or high-pressure hot water
Turf: Remove it (then, bring in earth from other places)
Concrete surface: Wash off with hot water or high-pressure hot water
Gravel: Comb out and wash off (then, bring in earth from other places)
Interlocking bricks: Electric planer and wash with high-pressure hot water

Fig. F.7. Use of decontamination methods for housing and land structures (Ishida, 2012).

- *Garden trees*: Trim and remove leaves and branches. Remove turf or area near base of trees to depth of 5 cm. Remove lichen on bark of trees by high-pressure washing.
- *Garden soil*: Remove the surface either manually or by machine and bring new topsoil.
- *Shed*: Wash off with hot water or high-pressure hot water.
- *Turf*: Remove it and bring in new turf.
- *Concrete surface*: Wash off with hot water or high-pressure hot water. Shot blasting and ice blasting are also effective.
- *Soil in playgrounds*: Remove surface soil using heavy machines like motor graders.

Where appropriate, a dam was provided to collect wash water, which was treated with zeolite to remove radioactive materials and avoid secondary contamination. Dams can be made from sponges with enhanced cesium adsorbing properties.

F.3.3.2 *Decontamination of Roads, Paved Surfaces and Gutters*

- *Roads*: High-pressure washing and brush washing are possible. However, washing with spin jet devices or function recovery vehicles have distinct advantages because the wash water is simultaneously collected.
- *Paved surface*: Remove a few millimeters of surface using a track saw cutting device. After cutting, overlay with dense

granular compressed concrete. If large cutting machines cannot enter, surface cutting by shot-blasting may be undertaken.
- *Gutters*: High-pressure washing.

F.3.3.3 *Decontamination of Woodland*

- *Undergrowth*: Remove humus layer and mow undergrowth. Remove fallen leaves and twigs by vacuum suction.
- *Trees*: Prune, using special equipment for inaccessible places.

Preference is to remediate forest in vicinity of urban settlements and agricultural land.

F.3.3.4 *Decontamination of Farmland*

- *Soil*: Removal of surface soil layer with heavy machinery such as shoveling equipment. Another possibility is to spray fixation agents and peel off the surface soil.

While removal of topsoil is the most efficient countermeasure to reduce radioactive cesium in the soil, it has the disadvantage in generating large volumes of waste (up to 400 ton per hectare for 4 cm removal of topsoil). Deep plowing is a promising and less expensive option for decontaminating soils and does not produce waste.

F.3.3.5 *Volume Reduction Techniques for Waste*

- *Plants*: Grinding plants reduces volume (*e.g.*, 27.4 m^3 reduces to 3.8 m^3).
- *Soils*: "Scan and sort" is carried out on the surface soil removed (where activity concentrations are less than an agreed value, the soil is returned to where it was removed).
- *Water (low levels of contamination)*: Columns filled with activated carbon to capture suspended material and other columns filled with zeolite to absorb radiocesium.
- *Water (high levels of contamination)*: Mobile equipment using high performance zeolite-series resin.

The various decontamination technologies deployed have shown varying levels of removal efficiency, so care should be exercised to ensure that sufficient efficacy is achieved during cleanup. Some examples of the information obtained in the decontamination effort are shown in Table F.5.

TABLE F.5—*Examples of the result of decontamination efforts in towns adjacent to Fukushima.*[a]

Working Points	μSv h^{-1}		Decontamination Efficiency (%)
	Before	After	
Naraha Town			
• asphaltic pavement	0.77	0.50	35
• rooftop of building	0.29	0.24	17
• near outer wall of building	0.41	0.32	22
Tomioka Town			
• asphaltic pavement	7.75	3.97	49
• lawn in a parking lot	9.62	2.65	72
• planted area	8.30	4.18	50
• lawn	8.70	2.27	74
• graveled area	5.59	1.33	76
• rooftop of building	5.74	3.57	38
• near outer wall of building	2.91	1.88	35
Namie Town			
• asphaltic pavement	0.50	0.33	34
• rooftop of building	0.32	0.25	22
• near outer wall of building	0.35	0.32	9
Iitate Village			
• asphaltic pavement	2.94	1.96	33
• stone pavement	3.41	1.78	48
• planted area	4.08	1.92	53
• grass land	4.24	1.52	64
• lawn	4.39	0.96	78
• near outer wall of building	2.12	1.25	41

[a] Cardarelli, J.J., II (2012). Presentation at the W*ide Area Restoration and Resiliency Program Capstone Conference* (U.S. Environmental Protection Agency, Cincinnati, Ohio).

F.3.4 *Radioactive Waste*

Large quantities of radioactive waste will be generated from a massive remediation effort in an area that is widely contaminated by an incident (Section 4). The materials generated are to be collected, characterized and processed as required. For materials that contain varying levels of radioactive contamination, proper storage and final disposal as radioactive waste will be required. The quantities of waste generated generally depend on the extent and depth of the surface contamination, the affected environment, the land-use options, and the remedial decisions associated with the affected area. Specifically, the cleanup criteria directly influence the quantity of the waste, by determining the size of the cleanup area (Appendix F.3.1).

As an example, based on nine reference cases of decontamination relative to the Fukushima nuclear accident, the preliminary estimate of the waste volume ranges from 5 to 29 × 10^6 m^3 (IAEA, 2011b). This volume is in addition to the estimated 2.3 million tons of contaminated debris collected from the destruction caused by the tsunami.

Thus, the primary challenge in waste management strategy in the remediation effort is the effective management of very large volumes of generated waste and the determination of the locations for interim storages (Figure F.8), as well as final disposal of the waste. Since the majority of the waste will likely be only slightly contaminated, it is imperative that a strategy to characterize the waste properly for appropriate disposition be developed. In general, there are three such categories of waste as suggested by IAEA (2011a):

- waste that can be disposed with unconditional clearance from regulatory control (for reuse or recycle without restrictions);

Fig. F.8. Temporary storage for removed topsoil from a paddy field at a demonstration site in Iitate Village (IAEA, 2011b).

- waste that can be disposed with conditional clearance with certain arrangements (such as disposal in designated municipal landfills that meet the regulatory requirements); and
- waste that are characterized as radioactive waste and must be disposed of at licensed radioactive waste facilities.

IAEA cautions against any approach that is based on over-conservatism in determining the levels for these three categories of waste materials, citing enormous challenges for timely establishment of a new waste disposal infrastructure in order to expedite the remediation actions. Furthermore, the potentially huge costs that are required to manage the radioactive waste will result in significant delays in the remediation effort to allow a timely recovery of the community. A more in-depth discussion about the radioactive waste disposal system in the United States was presented in Appendix B.

F.4 Radiation Doses

F.4.1 *Individual Doses*

One primary objective of remediating contaminated areas is to reduce individual doses through the optimization process. To accomplish this, several important factors need to be taken into account. First, unlike typical exposures from a single contaminated area (such as a piece of land or a facility), individuals in a wide-area contamination situation will likely receive exposures through multiple exposure scenarios throughout the year. Elevated contamination levels will likely exist throughout the community, and so potential exposures may be incurred by individuals (*e.g.*, in their residences, community centers, roads, work places, schools). Thus, the annual individual dose may be represented by a collection of exposures from multiple scenarios (Figure F.9).

$$D_\mathrm{T} = \sum_{\mathrm{i}=1}^{n} f_\mathrm{i} \times D_\mathrm{i}\,, \tag{F.1}$$

where:

D_T = total dose received by the individual receptor

f_i = occupancy frequency for Scenario i

D_i = dose received for Scenario i, as a function of contamination level and pathways

An individual-related exposure from multiple scenarios in wide-area contamination.

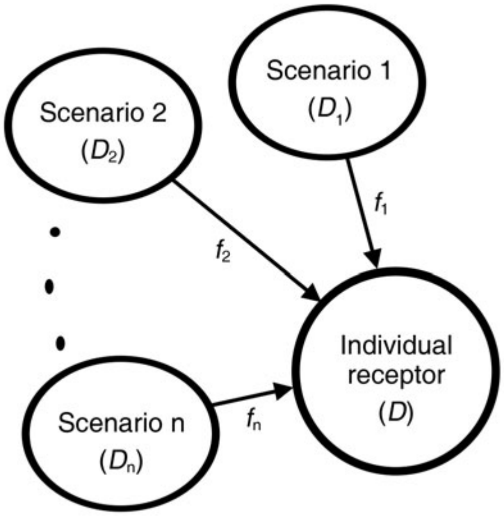


Fig. F.9. Contributions to individual doses from multiple scenarios in wide-area contamination.

Each exposure scenario may be characterized by a specific land use (*e.g.*, represented by a set of exposure parameters including occupancy frequency) in the contaminated areas that could be accessed by an individual throughout the year. Thus, for a population that lives and conducts their daily activities in a contaminated zone, the calculation of annual doses should consider the various scenarios and related activities. The available pathways associated with the exposures would generally consist of external dose due to contaminated structures or lands, and internal dose due to inhalation of contaminated air and ingestion of foods grown from contaminated lands. As an example, the preliminary assessment of individual doses from the primary pathways from the Fukushima Dai-ichi nuclear accident has been performed by WHO (2012). The WHO assessment has not taken into account the remedial actions to be performed for the late-phase recovery.

The two primary approaches for remediation considerations to reduce the individual doses are to:

- reduce or limit the accessibility (*i.e.*, lowering the frequency f_i in Equation F.1) to a specific exposure scenario (specifically for those associated with high doses); and
- reduce the dose (D_i in Equation F.1) by removing or reducing the radioactive sources (through decontamination), or modifying the pathways (through imposing appropriate controls).

Such dose reduction measures would form the basis for designing the remediation options (Appendix F.3.2) as well as for developing a long-term management strategy for coping with residual contamination.

There are several important aspects to be considered in strategy development:

- It will be difficult to assess individual doses with a high degree of precision unless all exposure scenarios are well defined and characterized for the affected community.
- Remediation decisions will influence the individual doses in different ways, so an overall strategy is needed to prioritize the remediation actions with objectives to achieve dose reduction.
- Dose assessment should be based on realistic assumptions and parameters to avoid skewing the decision making.
- Individual doses should be reassessed during the remediation process, and also be evaluated periodically for long-term monitoring and management afterwards.

Combined remediation actions and natural factors [*i.e.*, radioactive decay and weathering effects (Appendix F.2)] will serve to reduce the individual doses over time. However, some individual doses may increase temporarily due to specific activities such as handling and storage of radioactive waste during and after remediation actions, as well as potential reconcentration of radioactive contamination due to weathering (such as runoffs) or resuspension.

F.4.2 *Collective Doses*

The collective dose is an important instrument for optimization, specifically for comparing radiation protection technologies and procedures (ICRP, 2007). It represents the product of those exposed in a population and the associated dose levels. The collective dose also serves as a very useful tool for the cost-benefit analysis (Appendix F.5.2), a key component in the optimization process. Therefore, reduction of the collective doses (and consequently individual doses) is an important measure in gauging the effectiveness of remediation actions as well as the long-term management of the recovery.

As in the case for individual doses, much uncertainty is involved in assessing the collective dose. It is thus important to focus on exposure scenarios for which significant collective dose can be meaningfully assessed. These scenarios include relatively large population groups with specific geographic distributions, users of major public infrastructures or places, specific age groups (*e.g.*, elderly residents), or sensitive populations (*e.g.*, children). Realistic assumptions should be made on dispersion of the parameters used for the scenario and estimated sizes of the populations involved. Such examples may include populations in metropolitan centers, major shopping malls, traffic arteries, schoolyards (protection of children); some of these have received priority considerations in recent remediation efforts in Fukushima prefecture and environs (IAEA, 2011b). Because systematically reducing collective doses to the various population groups may also reduce individual doses, as discussed above, the collective dose serves as a key input to decision making for prioritization of the remediation actions.

F.4.3 *Long-Term Dose Reduction*

The optimization process is designed to provide a systematic approach to expedient reduction of individual doses to the affected populations living under existing exposure situations that takes into account the many considerations discussed in Section 4. The strategy is to reach an optimized decision process as discussed in Section 5. The priority of remediation is to focus on high collective-dose scenarios for a systematic approach to reduce individual doses, as discussed above. Consequently, the long-term strategy, as illustrated in Figure F.10, includes:

- systematically lowering the individual doses to reach an optimized level;
- continually lowering the average individual doses by reprioritizing the remedial actions against the highest-dose scenarios until the objectives of the optimization are reached; and
- implementing long-term monitoring to further manage the residual contamination.

As discussed earlier, remedial measures include limiting the accessibility (by imposing institutional controls), modifying the relevant pathways (such as limiting intakes of contaminated foods), and taking active remediation actions (such as decontamination). It is necessary to continually obtain and update status information in cooperation with the affected populations and stakeholders to determine if further protection strategies (decontamination activities, food restrictions, or additional controls) are needed until optimization is deemed to be achieved. Details regarding the application of long-term monitoring are discussed in Section 6.

F.5 Optimization Considerations

F.5.1 *Multi-Attribute Approach*

Evaluation of options for the late phase of recovery after a nuclear or radiological incident should balance all of the relevant

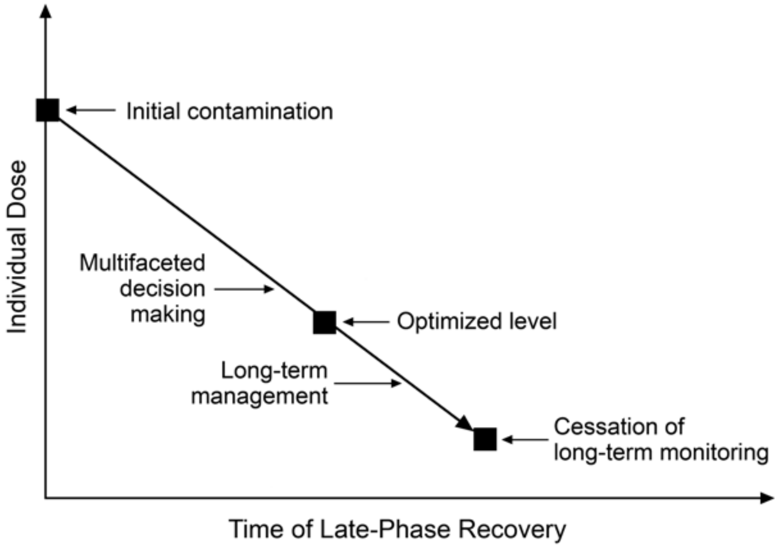


Fig. F.10. Long-term management strategy in the optimization process.

factors, including those listed in Table F.1. The attributes listed are shown for illustrative purposes, may be interrelated or overlapping and hence, may be grouped or divided in an actual optimization process. The attributes considered need to be selected and prioritized for decision considerations.

The complexity of the optimization deliberation process is further illustrated by the example shown in Figure F.11 where the essential elements to identify cleanup options are delineated for industrial property. Considerations for such properties generally include:

- health risks (for both radiological and nonradiological risks);
- governmental decisions (how cleanup effort can be facilitated);
- social impact;
- economic feasibility; and
- environmental impact.

It is conceivable that many of the decisions in this process may involve an array of stakeholder groups with different interests and concerns. For example, demand for a rigorous remediation might be counterbalanced by an increasingly steep resource demand and strained financial support, as well as the possibility of generating large quantities of radioactive waste. Such issues are to be addressed in the pre- and post-planning processes described by the NDRF (FEMA, 2011a), and as addressed in Appendix F.5.3.

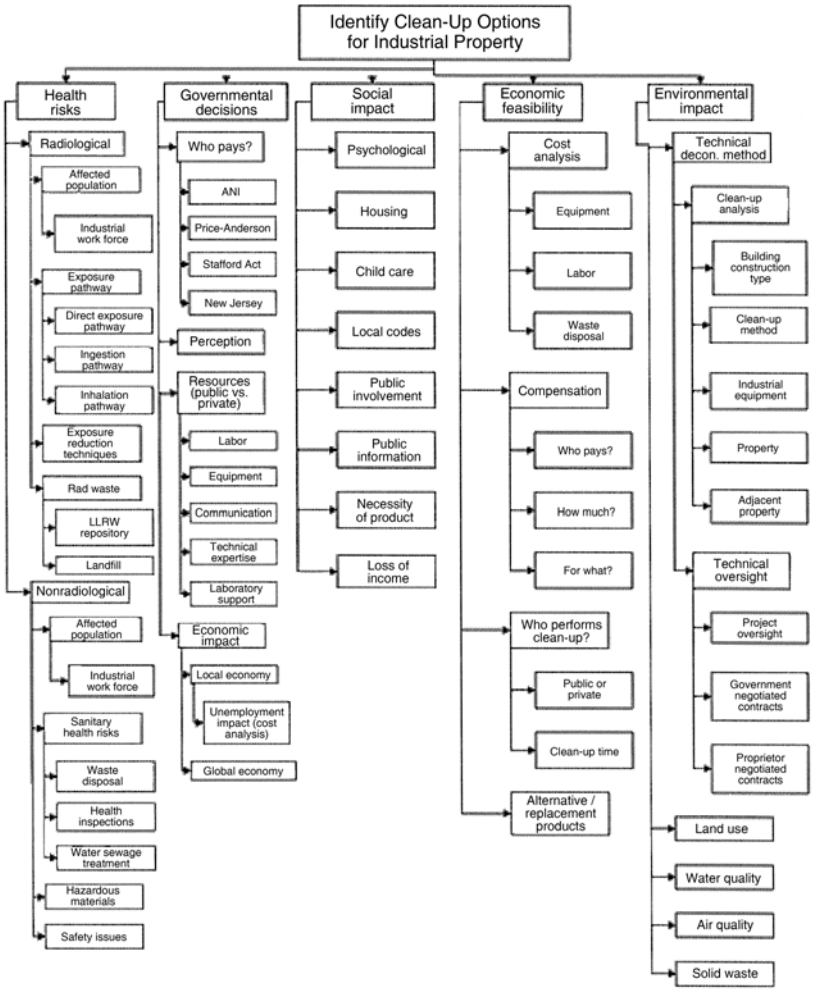


Fig. F.11. Industrial property matrix (Bureau of Nuclear Engineering, New Jersey Department of Environmental Protection, Trenton).

The multi-attribute approach will necessarily include complex analyses to support decision making, such as the cost-benefit analyses, and thorough vetting of the process by the stakeholders, as discussed below.

F.5.2 *Cost-Benefit Analysis*

As described in Section 5.5.1.1 and also in Appendix D, cost-benefit analysis is a tool to support decision making by quantifying (frequently by monetizing) positive and negative impacts of options to identify which one maximizes benefits or minimizes costs. The net benefit of an activity may be expressed mathematically in the following manner:

$$B = V - (P + X + Y), \tag{F.2}$$

where:

B = net benefit of the activity or net cost if B is negative
V = gross benefit of the activity
P = basic production (*e.g.*, remedy implementation) costs
X = cost of achieving a selected level of protection (the cost of remedial measures to reduce radiation risk)
Y = cost of radiation detriment resulting from the activity at the selected level of radiation protection

In general application, B should be positive for an action to go forward. However; in responding to a radiological emergency, costs may exceed benefits for all options available (B will be negative) and the goal would be to identify the option with the lowest cost (negative B closest to zero).

In the typical application of cost-benefit analysis in the optimization of radiation protection, cost Y has two basic components, a health detriment and a nonhealth detriment and is monetized as a function of collective dose. It is determined by:

$$Y = {}'\Upsilon\, S + \beta\, \Sigma_j\, N_j\, f_j\, (H_j), \tag{F.3}$$

where:

$'\Upsilon$ = health detriment cost coefficient (dollars person-Sv^{-1}) collective effective dose
S = collective effective dose (person-Sv)
β = nonhealth detriment cost coefficient (dollars person-Sv^{-1}) collective effective dose
N = number of individuals exposed
f = function of the individual doses, which would depend on risk aversion attitudes and regulations or company policies
H = mean effective dose (sievert) where j represents a particular group of individuals for N, f, and H

Figure F.12 shows the classic relationship between cost and dose reduction where the sum of "cost of protection" (X) and the monetary value of the detriment (Y) and the lowest cost represents the optimum or most cost-beneficial solution. In a cleanup or remedial action, Y includes the risk from exposure to residual radioactive material not mitigated by the response action. The benefit of

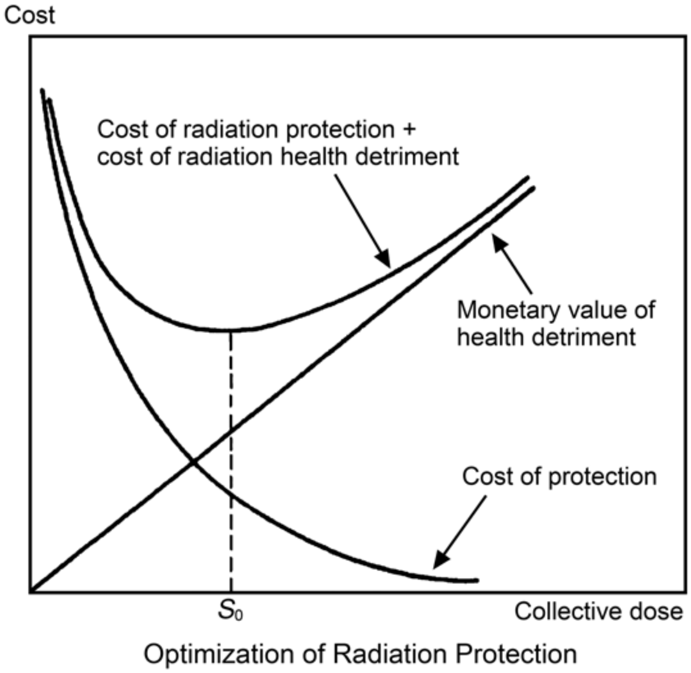


Fig. F.12. Cost-benefit relationship using collective dose as a primary measure (S_0 is the lowest cost on the total cost curve) (Ahmed and Daw, 1980).

the dose reduction accomplished by the action may be included in the gross benefit B in Equation F.2 and its monetary equivalent evaluated similar to Y in Equation F.3, or it may be included as a negative cost in Y.

However, in applying these techniques to actions responding to a nuclear or radiological incident, it must be recognized that not all costs or benefits are directly proportional to collective dose and additional costs may need to be included in the analyses. Examples include the cost of lost services, the cost of lost employment, the cost of lost ecological or cultural resources, and so forth. These costs will need to be addressed as part of P in Equation F.2. In addition, both the radiological and nonradiological risks to the responders conducting remedial measures will need to be included as costs while the doses averted by the actions taken are benefits or negative costs.

Not all benefits or detriments of an action can be monetized and in such cases, it may be useful to combine cost-benefit analyses with Multi-Attribute Utility Theory (MAUT) or other techniques to evaluate the options more completely. It should also be noted that Figure F.12 illustrates a continuous cost and presents a simplistic situation where the optimum alternative S_0 is identified as the lowest cost on the total cost curve. This is rarely the case in evaluating options for response or remedial action options. In most situations, there are a limited number of discrete options available. For instance, as with the Fukushima Dai-ichi accident, given an incident that caused wide-area contamination, the initial response may be to take actions to address public property such as schools, fire stations, government centers, and so forth. Such actions will result in clean or partially remediated islands within a contaminated area, and because the contamination is primarily on the surface, removal actions will result in zero residual activity in the area remediated and the residual risk (cost) will be driven by the surrounding contamination. The size of the buffer area cleaned, rather than cleanup level would drive the residual dose. Assuming a large-scale ^{137}Cs contamination incident, screening calculations using RESRAD-OFFSITE indicate total removal of residual activity from ~4 ha of land surrounding the subject facility could result in a dose reduction in excess of 40-fold, while removal of surface soil from only ~0.8 ha would produce about half that reduction (about 20-fold). Other options to reduce dose include blending of the surface contamination in the soil, which provides for self-shielding by the soil. Plowing to 15 cm depth can reduce projected doses from that soil by about half and mixing soil to a depth of 1 m reduces doses by a factor of 10.

It is assumed that all options include remediation of the structures. The cost per hectare of soil removal and disposal will be about equal for the removal options and the cost for soil mixing in the second two options will be the primary costs. Disposal costs include the removal, packaging, any necessary temporary storage, and transport to permanent disposal. In this simple illustration, costs such as for transport or establishment of waste disposal or storage areas are ignored, because they are so variable and option driven. Also many factors that may be important to the acceptability of any action such as stakeholder acceptance, ecological and cultural resource valuation, and value of the service provided by the facility are not addressed. But as noted above, in a real optimization cost-benefit analysis their value would need to be assessed or be incorporated through combination with another tool like MAUT (Appendices C and F.5.1).

Figure F.13 is presented to illustrate the results of the cost-benefit analysis of the five discrete options discussed in Table F.6. Option E, deep mixing is the most cost beneficial of the five but it is

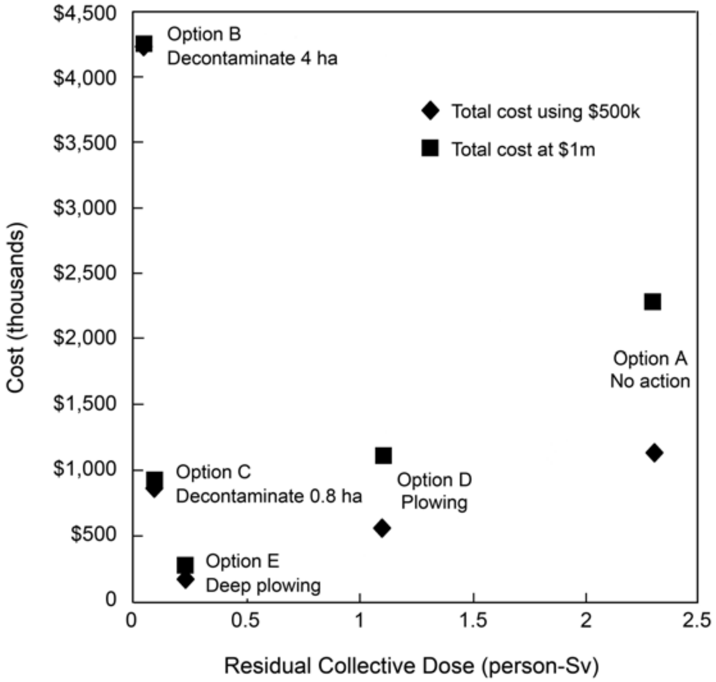


Fig. F.13. Illustrative total cost-benefit chart for options in Table F.6 (upper and lower data points for each option show impact of doubling collective dose monetary equivalent).

- This chart compares total cost (cost of action plus residual dose detriment) for each option considered. The red data points show impact of doubling the collective dose monetary equivalent. Only the relative ranking of Options C and D change.
- Land surface area is expressed in units of hectare (ha). 1 ha (10,000 m^2) = 2.47 acres.

closely followed by Option D (shallow mixing) and Option C (remediating 0.8 ha). Option B (remediating 4 ha) results in the lowest residual dose but implementation and disposal costs make it the least cost-beneficial of the five options, even less than no action (Option A). The chart also illustrates the impact of the monetary equivalent on the cost benefit. The upper data points for each alternative demonstrate the impact of doubling the collective effective dose monetary equivalent (*e.g.*, going from $500,000 to $1,000,000 person-$Sv^{-1}$). As Figure F.13 illustrates, the impact is minimal on the decision. Alternative E is still the most cost beneficial. Options D and C change places in the order but the difference is insignificant. The no-action alternative (Option A) doubles in total cost and the

TABLE F.6—*Illustrative cost-benefit analysis data.*

Option	Residual Dose (person-Sv per 100 Bq g^{-1}) ^{137}Cs, and Costs	Remedy Implementation Costs	Waste Management Costs	Benefit (dose reduction only)
A: No Action – continue to use as is	2.3 $1,100,000	$ 0	None	None
B: Decontaminate structure and clean ~4 ha	0.045 $22,000	High $2,400,000	High 6,100 m^3 $1,800,000	$1,100,000
C: Decontaminate structure and clean ~0.8 ha	0.09 $45,000	Moderate $480,000	Moderate 1,200 m^3 $360,000	$550,000
D: Decontaminate structure and plow ~4 ha to 15 cm	1.1 $570,000	Low $20,000	Low Few hundred cubic meters Tens of thousand $	$450,000
E: Decontaminate structure and mix soil for ~4 ha to 1 m	0.23 $110,000	Low $60,000	Low Few hundred cubic meters Tens of thousand $	$1,000,000

impact on Option B is insignificant because remedial action and disposal costs greatly overshadow the radiological detriment. The lesson here is that in many cases, the cost-benefit is not very sensitive to the monetary value of the collective dose. The other major consideration is stakeholder preferences. It is likely that the removal options may be more desirable to some and that factor could cause Option C to be selected. Even though it is the lowest dose option, it is not likely that Option A could be justified.

Although individual dose is not specifically evaluated in the cost-benefit analysis, it is a factor that will need to be considered in assessing the acceptability of the various options. In Figure F.13, it was assumed that the subject public facility and the surrounding areas were initially contaminated to ~100 Bq g^{-1} to about a 2 cm depth. Options B (removal of ~4 ha), C (removal from ~0.8 ha), and E (mixing to 1 m) all reduce doses to <1 mSv y^{-1} individual effective dose, which is the goal for school grounds for the Fukushima Dai-ichi accident. No action and the shallow mixing options both would likely exceed that level and therefore, if the 1 mSv y^{-1} individual effective dose goal was deemed an essential criterion for the remedial action, both would be screened out. A minor increase in mixing depth (*e.g.*, 35 cm instead of 15 cm) for Option D could result in it meeting the 1 mSv individual effective dose criterion. If the criterion were set at 10 mSv y^{-1} individual effective dose, at the assumed surface concentration for this illustration, no options would be excluded.

If the initial concentration of ^{137}Cs surface soil contamination were higher (*e.g.*, 200 Bq g^{-1} at 2 cm) neither Options A or D would meet the 1 mSv y^{-1} individual effective dose criterion because of the substantial increase in detriment, and the cost of Option A would increase to a level approaching Option B on Figure F.13. Option D would significantly increase in cost such that Options C and E would be the two lowest cost alternatives and the difference between the two would be smaller.

If the soil contamination were at 500 Bq g^{-1}, only Options B and D would meet the 1 mSv y^{-1} individual effective dose criterion and although all but Option A (no action) could meet the 10 mSv y^{-1} criterion, Option D (shallow mixing) projected doses begin to approach 10 mSv y^{-1}. At 500 Bq g^{-1}, the cost of Option A increases significantly to be the highest of the five options. Option C (~0.8 ha removal) and Option E (deep mixing) remain the most cost-beneficial and the shallow mixing Option D cost to benefit ratio begins to approach Option B (~4 ha removal). Because the projected doses are so much higher at this level of contamination, the impact of the monetary equivalent for collective dose will also be more significant. At this level, doubling the value of the monetary equivalent could make Option C more cost beneficial than Option E, and Option B more cost-beneficial that Option D.

In summary, this analysis demonstrates that many factors can influence the optimization decision process. It is important to consider incident and location-specific parameters appropriately when applying cost-benefit analysis. It is also important to recognize that some factors may not be appropriate to address in the analysis and may need to be included in the optimization process *via* another one of the tools discussed in Appendix D.

In addition to supporting cost-benefit analyses, these other tools may be appropriate to support optimization decisions on their own. They can be especially important in the application of optimization in planning for a response where detailed site- or incident-specific information is not available. Table F.7 illustrates how these tools might be used in conjunction with the optimization process to develop guidelines for protective actions that could be applicable to release or control of private property such as vehicles and equipment. The analysis indicated that for a large incident affecting hundreds or thousands of vehicles, there would not be resources available to survey all affected vehicles. An alternative process used pathway models to identify appropriate protective actions that would ensure that the PAGs in DHS (2010a) Planning Guidance would be met, and then models and screening measurements to identify zones where vehicle contamination would likely fall within the defined surface activity ranges. In the example, clearance guidelines and associated protective actions were developed to provide reasonable assurance that members of the public will be protected. The surface activity guideline values and associated protective actions include: no action necessary, release for self-remediation, and controlled remediation. Table F.7 is the result of a simple pros and cons analysis. The issue was how to release private vehicles and equipment that might be contaminated following a nuclear or radiological incident. The first alternative considered where to require surveys of all impacted vehicles and establish decontamination programs to clean them to dose-based levels predicated on the American National Standards Institute (ANSI) standards. This alternative was viable for a small incident that might involve a few tens of vehicles or less but it was not feasible for large incidents involving hundreds or thousands of vehicles. Although a cost-benefit assessment could have been used to demonstrate that this option was not cost-beneficial, such an analysis was unnecessary because regardless of cost, the radiological control resources simply were not available to accomplish such a program in a timely manner.

TABLE F.7— *Reference levels for operational guidelines and recommendations for protective actions.*

Radionuclides	Units	Alpha Particles[a] (^{241}Am, ^{252}Cf, ^{244}Cm, ^{210}Po, ^{238}Pu, ^{239}Pu)	Beta Particles/ Gamma Rays[a] (^{60}Co, ^{137}Cs, ^{192}Ir, ^{90}Sr)	Protective Action Recommendation
No-Action[b] ≤10 × ANSI screening levels[c]	Bq cm^{-2} dpm (100 cm^{2})$^{-1}$	0.1 – 1 600 – 6,000	1.0 – 10 6,000 – 60,000	None; property may be used or released for general use without restriction.
Self Remediation[b] 10 to 200 × ANSI screening levels[c]	Bq cm^{-2} dpm (100 cm^{2})$^{-1}$	1 – 20 6,000 – 120,000	10 – 200 60,000 – 1,200,000	May be used or released subject to cleaning the property by owner/user; by rinsing/washing, using standard household techniques. Cleaning should be done within days of removal from impacted areas.
Control or monitored remediation[b] ≥200 × ANSI screening levels[c]	Bq cm^{-2} dpm (100 cm^{2})$^{-1}$	≥20 ≥120,000	≥200 ≥1,200,000	Maintain under control or supervision of radiation safety personnel or recommend decontamination in monitored systems to the no-action levels.

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[a] Although established based on dose assessments the basis of the groupings in the table was supported by the original ANSI N13.12 (ANSI/HPS, 2013) because the evaluation was completed prior to the issuing of the 2013 update. The radionuclides in each group are based on similarity of exposure scenario results. In the recently updated ANSI N13.12 (ANSI/HPS, 2013) the screening levels for clearance of ^{60}Co and ^{137}Cs were revised down to Group 1 levels; all other radionuclides in this example remained the same. The table continues to include ^{60}Co and ^{137}Cs in Group 2 because the analyses supporting this example, for this situation, derived from DOE operational guidelines indicate they meet the guidance in the DHS PAGs and operational guidelines implementation.

[b] Assessment methods for the "No-Action" and "Self-Remediated" guidelines include direct measurement (survey or sampling), inference from modeling, indirect measurement (measurements made on the street), proximity to the incident and the associated plume, or expert advice. For areas likely to require control or monitored remediation the preferred assessment method is direct measurement (survey or sampling). However, statistical sampling may be used if it demonstrates reasonable uniformity of results.

[c] ANSI N13.12 screening levels are: Group 1 (0.1 Bq cm^{-2} or Bq g^{-1}) and Group 2 (1 Bq cm^{-2} or Bq g^{-1}). Levels are designed to be protective of a TEDE to an average member of the public of 10 μSv y^{-1}.

The alternative approach determined to be viable was to use modeling to support identification of zones within the impacted area where most could be cleared for normal use with no protective actions required, zones where vehicles could be released to members of the public where they would be directed to wash the vehicles as soon as practical before continued use and then zones where contamination was likely to be high enough to require embargoing of the vehicles until they could be decontaminated at a central facility. The analysis used the DOE operational guidelines manual and RESRAD to assess doses from multiple pathways and DHS (2008a) Planning Guidance to select dose criteria. The pathways assessed included dose to members of the public during cleaning, potential impacts of residual contamination resulting from the self-decontamination, and effects of run-off. The dose analysis also considered the possibility that members of the public would not complete the self-remediation in a timely manner but would continue to drive the car. The reference levels presented in Table F.7 illustrate the result of this type of planning analysis. Response planners may select different parameters from those used in this illustration and establish different groupings. The example illustrated in Table F.7 establishes three criteria zones to provide protective action guidance that is consistent with DHS Planning Guidance including:

1. *No-Action Zone*: These include all areas beyond the impacted area and constitute areas where, based on modeling and an appropriate level of statistical sampling or measurement, personal property in the area is likely to have contamination of little or no significance [<10 times ANSI N13.12 (ANSI/HPS, 2013)[11] screening levels (Section 6)]. Aggressive public information programs should be implemented to assure members of the public that property in these areas is not significantly affected and may be safely used. Outreach programs should stress the fact that property from these areas need not be surveyed or characterized. Such actions would consume resources that are necessary to address concerns for property in the impacted and highly contaminated areas or for other actions that avert serious consequences. The major point to be made is that property hazards in these areas are negligible and of

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[11] The dose analyses supporting this example were completed using the groupings in the 1999 version of ANSI N13.12. In the 2013 version, ^{60}Co and ^{137}Cs were moved from Group 2 ($1\ \text{Bq cm}^{-2}$) down to Group 1 ($0.1\ \text{Bq cm}^{-2}$). However, the dose assessment did not justify changing the values in Table F.7.

low priority; having to conduct significant assessments would detract from efforts to avoid real hazards.

2. *Impacted areas (Intermediate Zone)*: This zone includes those areas that can or rather are likely to exceed 10 times the ANSI N13.12 screening levels (beginning at the boundary of the no-action zone) to a point where property could be contaminated to more than 200 times the ANSI N13.12 screening level. The boundary for this zone should be defined through measurement and/or modeling. Validation of measurement for a number of vehicles and other equipment is recommended. The protective action recommendation for material in these areas is for cleaning by the owner/user as soon as practical, rinsing, washing, or other appropriate cleaning should be done within days of removal from impacted areas. However, based on analyses, even use for extended periods (months) of vehicles and other material and equipment at these levels without cleaning would not be likely to cause doses in excess of 1 mSv TEDE and they would not exceed the relocation PAG. Outreach programs and public information should stress that these self-administered protective actions will be effective and protective and do not pose any risk of substantial radiation exposure to the user.
3. *High Contamination Zone (areas where contamination of property is reasonably expected to be in excess of the "control or monitored remediation" guidelines (more than 200 times ANSI screening values)*: In areas where contamination is sufficiently high so as to result in surface activity levels on vehicles, equipment or materials, continued long-term use of such materials should be discouraged. The recommended protective action is that the material be controlled and not used until its radioactive content is characterized and/or it is taken to a decontamination area that is monitored or supervised by radiation protection personnel and decontaminated to levels that approximate or are less than the No-Action levels. Although "self-remediation" would likely be able to adequately decontaminate the property, these surface activity levels (greater than 200 times the ANSI screening levels) have the potential to contaminate areas where the property is being cleaned and waste from washing a large number of vehicles or equipment could result in significant contamination at treatment plants or sewer discharge points that are not released to a treatment plant, hence, monitored decontamination is recommended.

> In addition, at these levels extended use of the property before decontamination, in some cases, could result in doses that exceed the relocation PAGs and the 1 mSv y^{-1} TEDE level. It is recommended that decontamination centers be established as soon as practical to deal with such vehicles and equipment and that the vehicles be surveyed or at least spot checked after decontamination and the level of contamination in wash water or cleaning media be assessed before disposal to determine the appropriate disposal alternative. Recognizing that much of the property in this zone will be difficult to control and that implementation of the protective actions will also be difficult, outreach programs and public information should stress the value of public protection and contamination control and that owners and users of such property should abide by the recommendations and directions of the authorities and avoid any extended use of vehicles, equipment or material until it is adequately characterized as safe or decontaminated in a monitored decontamination location.

This example is presented to illustrate how the optimization process can be used in response planning. NCRP is not necessarily recommending these levels for general application in emergency response, and response planners should conduct their own assessments using these tools to determine the screening criteria that would best meet their needs, considering the various attributes that will contribute to the decision. Although many decisions will require site- or incident-specific data to determine the optimum response actions, there are assessments such as this example that can be made during the response planning that can effectively expedite the response.

F.5.3 *Stakeholders Involvement in Recovery*

This appendix subsection supplements the general guidance discussed in Section 5.6.2 on stakeholder involvement in decision making, and particularly for those activities associated with recovery from major disasters.

In the United States, NDRF (FEMA, 2011a) provides guidance to promote effective recovery, particularly for large-scale incidents. The NDRF guidance enables effective recovery support to disaster-impacted states, tribes and local jurisdictions. Recovery begins with pre-disaster preparedness and includes a wide range of planning activities. The NDRF clarifies the roles and responsibilities for stakeholders in recovery, both pre- and post-disaster. It recognizes that when a disaster occurs, it impacts some segments of the population more than others. The NDRF advances the concept that recovery encompasses more than the restoration of a community's physical structures to its pre-disaster conditions. Of equal importance is providing a continuum of care to meet the needs of the affected community members who have experienced the hardships of financial, emotional or physical impacts as well as positioning the community to meet the needs of the future.

The NRDF recognizes that all recovery activities must be community based; the local community identifies needs and advances the initiatives, which are coordinated, facilitated and supported by the state, federal and tribal governments.

F.5.3.1 *Roles and Responsibilities of Stakeholders*. All decisions made are to actively engage the relevant stakeholders, with their roles and responsibilities discussed below.

- *Individuals and households*: Need to plan and sustain themselves in the aftermath of a disaster to prepare and enhance their ability to undertake their own recovery and help shape the future of the community's recovery.
- *Private sector*: Plays an important role in community's recovery. The private sector owns and operates the nation's critical infrastructure (such as financial support and providing power supply), as well as offering employment and supporting the local tax base. It serves as a stabilizing force for a resilient community. Examples of the private sector include:
  - business community;
  - critical infrastructure owners and operators; and
  - banks and insurance companies.
- *Nonprofit sector*: Plays a vital role in the recovery of the impacted community, as their value resides in community recovery planning, case management services, volunteer coordination, behavioral health and psychological and emotional support, technical and financial support, housing repair and construction, and project implementation. Examples of nonprofit organizations include:
  - volunteer groups;
  - faith-based and community organizations;
  - charities;
  - foundations and philanthropic groups;
  - professional associations (*e.g.*, trade and labor unions, consumers' rights)
  - academic institutions; and
  - local, state, tribal and federal governments.

F.5.3.2 *Recovery Core Principles*. The NDRF (FEMA, 2011a) is guided by nine core principles that, when put into practice, maximize the opportunity for achieving recovery success. How these principles interface with stakeholder engagement is indicated below.

- *Individual and family empowerment*: All community members must have equal opportunity to participate in community recovery efforts in a meaningful way.
- *Leadership and local primacy*: Local, state and tribal governments have primary responsibility for the recovery of their communities and play the lead role in planning for and managing all aspects of community recovery.
- *Pre-disaster recovery planning*: All stakeholders should be involved to ensure a coordinated and comprehensive planning process, and to develop relationships that increase *post-disaster* collaboration and unified decision making.
- *Public information*: Clear, consistent, culturally appropriate, and frequent communication initiatives promote successful public information outcomes. This ensures stakeholders have a clear understanding of available assistance and their roles and responsibilities; makes clear the actual pace, requirements and time needed to achieve recovery; and includes information and referral help lines and websites for recovery resources.
- *Unity of effort*: Common objectives are built upon consensus, and a transparent and inclusive planning process exists with clear metrics to measure progress.
- *Timeliness and flexibility*: The process strategically sequences recovery decisions and promotes coordination; addresses potential conflicts; builds confidence and ownership of the recovery process among all stakeholders; and ensures recovery plans, programs, policies and practices are adaptable to meet unforeseen, unmet and evolving recovery needs.
- *Resilience and sustainability*: The process engages in a rigorous assessment and understanding of risks and vulnerabilities that might endanger the community or pose additional recovery challenges.
- *Psychological and emotional recovery*: The process addresses the full range of psychological and emotional needs of the community as it recovers from the disaster through the provision of support, counseling, screening and treatment when needed.

F.5.3.3 *Recovery Success Factors*. Experience has shown that the presence of certain factors in a community can help ensure a successful recovery. How these factors interface with stakeholder engagement is indicated below.

- *Effective decision making and coordination*: Recovery leadership defines roles and responsibilities for all stakeholders and businesses, nonprofit organizations, and local community leadership who examine recovery alternatives, address conflicts and make informed and timely decisions that best achieve recovery of the impacted community.
- *Integration of community recovery planning processes*: Communities engage in pre-disaster recovery planning and other recovery preparedness, mitigation and community resilience-building work. The community develops processes and criteria for identifying and prioritizing key recovery actions and projects. The community's recovery leadership creates an organizational framework involving key sectors and stakeholders to manage and expedite recovery planning and coordination.
- *Well-managed recovery*: Well-established, pre-disaster partnerships at the local, state, tribal and federal levels, including those with the private sector and nongovernment organizations, help to drive a successful recovery.
- *Proactive community engagement, public participation, and public awareness*: Stakeholders collaborate to maximize the use of available resources to rebuild housing, infrastructure, schools, businesses and the social-historical-cultural fabric of the impacted community in a resilient manner; and to provide healthcare, access and functional support services. Local opinions are incorporated so that community needs are met in a more holistic manner. Running continuous and accessible public information campaigns to community members helps promote various recovery programs and the commitment to short, intermediate and long-term recovery.
- *Well-administered financial acquisition*: Community stakeholders need to possess an understanding and have access to broad and diverse funding sources in order to finance recovery efforts.
- *Organizational flexibility*: Organizational structures for coordinating recovery assistance are scalable and flexible, adapting and evolving, and efficient and effective.
- *Resilient rebuilding*: The community rebuilds a sustainable future inclusive of ecological, economic and local capacity considerations.

Appendix G

National Radiological Guidance on Late-Phase Recovery and Related Issues

G.1 National Response Framework

Responsibility for responding to disasters and emergencies, from the smallest incident to the largest catastrophe, including nuclear and radiological incidents, is currently specified under the National Response Framework (NRF) (DHS, 2008b). The NRF identifies the key response principles, as well as the roles of officials who organize responses ranging from local to regional levels. The scope and responsibilities of federal support are further prescribed in the Emergency Support Functions (ESFs) in the NRF. Fifteen ESFs are established for all FEMA-managed incidents with responsible federal agencies assigned to each (in collaboration with state and local governments). ESF numbers and titles include:

1. Transportation;
2. Communication;
3. Public Works and Engineering;
4. Firefighting;
5. Emergency Management;
6. Mass Care, Emergency Assistance, Housing, and Human Services;
7. Logistics Management and Resource Support;
8. Public Health and Medical Services;
9. Search and Rescue;
10. Oil and Hazardous Materials Response;
11. Agriculture and Natural Resources;
12. Energy;
13. Public Safety and Security;

14. Long-term Community Recovery; and
15. External Affairs.

For late-phase recovery issues, the responsibility for radiological cleanup falls under ESF #10 (Oil and Hazardous Materials Response) with EPA as the lead coordinating agency. For issues related to long-term cleanup, and depending on specific contamination situations, it is likely that the effort may overlap other support functions that are led by other agencies. For example, ESF #14 addresses long-term community recovery as led by FEMA, which would require close coordination with EPA in a particular response. However, this issue has been at least partially addressed by the NDRF.

G.2 National Disaster Recovery Framework

In 2011 FEMA issued its guidance report, the *National Disaster Recovery Framework* (NDRF) (FEMA, 2011a) which is intended to promote effective and efficient recovery, particularly for incidents that are large-scale or catastrophic for states, tribes, territorial and local jurisdictions. In its current form, the NDRF is intended for all disasters, from response to recovery and has not incorporated elements for incidents that involve hazardous materials, including radionuclides.

Like the NRF, the NDRF seeks to establish an operational structure and to develop a common planning framework. The focus of the NRF is on the response actions as well as the short-term recovery activities that immediately follow or overlap the response actions. In contrast, the NDRF provides tools to encourage early integration of recovery considerations into the operations in earlier phases of the response. It specifically replaces ESF #14 on long-term community recovery and includes recovery-specific leadership, organizational structure, planning guidance, and other components needed for individuals, businesses and communities.

The key elements of the NDRF include:

- core recovery principles;
- roles and responsibilities of recovery coordinators and other stakeholders;
- coordinating structure that facilitates communication and collaboration among stakeholders;
- guidance for pre- and post-disaster recovery planning; and
- the overall process by which communities can capitalize on opportunities to rebuild stronger, smarter and safer.

According to NDRF, the recovery process is described as a sequence of interdependent and often concurrent activities that progressively advance a community toward a successful recovery. The decisions and priorities set in the recovery process, however, affect the nature and speed of that recovery. Thus recovery activities are viewed in four distinct stages:

1. preparedness (ongoing);
2. short term;
3. intermediate term; and
4. long term.

The latter three stages are related to the post-incident response. It should be noted, however, that there are no clear-cut boundaries between the sort and intermediate, and intermediate and long term. The transition from one to the next will likely be highly dependent on incident- and site-specific conditions.

G.3 Federal Protective Action Guidance Specific to Nuclear or Radiological Incidents

In an effort to provide guidance for responding to terrorist attacks involving RDDs or INDs, DHS established an interagency working group in 2003, called the Consequence Management, Site Restoration/Cleanup and Decontamination Subgroup (of the Working Group on RDD Preparedness) to address the need for unified federal guidance on RDD-related issues, with participation from eight other federal agencies. Following several years of deliberation, the guidance entitled *Planning Guidance for Protection and Recovery Following Radiological Dispersal Device (RDD) and Improvised Nuclear Device (IND) Incidents*, was issued in 2008 (DHS, 2008a).The guidance provides PAGs to support decisions on actions to be undertaken to protect members of the public and emergency workers involved in the early and intermediate response phases of the incident. The guidance includes information and regulations published by EPA (1992), and also incorporates relevant recommendations from FDA and the Occupational Safety and Health Administration.

This 2008 DHS Planning Guidance was the first U.S. government guidance that specifically addressed the PAGs for terrorist attacks involving RDD or IND incidents. The response is, as usual, divided into three distinct, yet somewhat overlapping, phases of an incident: early phase, intermediate phase, and late phase. The general characteristics of these phases are discussed in Section 3.4.1. PAG guidance from DHS generally follows the 1992 EPA manual for nuclear accidents (EPA, 1992), except for response in the late phase.

The late phase represents the stage at which residual radiation levels from the incident are reduced to acceptable levels, allowing a return to a certain state of normalcy, which may last for many years following the incident occurrence. While the PAGs recommended by DHS contain specific dose criteria for response actions in both early and intermediate phases, they do not contain specific dose criteria for the late phase. Instead, DHS guidance recommends the late-phase cleanup be achieved through a site-specific optimization process.

Any criterion chosen will include consideration of existing federal statutory requirements on environmental cleanup (such as CERCLA and the NRC rule on license termination), along with other national and international recommendations. Numerous variables must be considered, such as the extent and type of contamination, goals for human and environmental health protection, and technological feasibility. The deliberation on cleanup goals and criteria will be conducted by a designated planning section unit, which will incorporate appropriate technical entities and stakeholders in the decision-making process of the emergency management structure.

For late-phase response (*i.e.*, long-term cleanup), the guidance prescribes a process for deriving a long-term plan, in lieu of a predetermined cleanup level, in which site-specific situations are properly balanced. This approach entails a site-specific optimization process for determining the appropriate cleanup criteria for the contaminated area. Compared to either early- or intermediate-phase responses, the decision makers will have more time to deliberate on the late-phase recovery issues.

To further support the proposed PAGs, an interagency team led by DOE was devoted to the derivation of the operational guidelines (Yu *et al.*, 2009) to implement the PAGs. The operational guidelines are derived levels of radiation or radionuclide contamination that can be measured in the field and compared to PAGs to determine quickly if protective actions are needed. The derived operational guidelines are largely based on the radiological criteria specified by the PAGs for both early phase and intermediate phase. Specific guidance for late-phase actions (*i.e.*, cleanup of contaminated areas) remains to be developed.

G.4 Current Statutory Cleanup Guidance and Requirements

The current guidance and criteria for radiological cleanup have been developed under various federal statutory requirements. As mentioned above, EPA has been assigned as the lead coordinating agency for ESF #10 (Oil and Hazardous Materials Response) in accordance with the NRF (DHS, 2008b). Therefore, it is likely that EPA would apply its statutory authority under the *National Oil* *and Hazardous Substances Pollution Contingency Plan* (CERCLA, 1980; EPA, 1994), as well as other cleanup authorities in environmental laws, to guide cleanup actions. However, these current criteria and requirements have not been fully evaluated for their applicability to address the issues associated with late-phase recovery from nuclear or radiological incidents (Chen and Tenforde, 2010; Elcock *et al.*, 2004; Eraker, 2004).

DHS (2008a) guidance is not intended to impact the existing EPA statutory programs, about which DHS states:

> "This Guidance is not intended to impact site cleanups occurring under other statutory authorities such as the Environmental Protection Agency's (EPA) Superfund [CERCLA, 1980] program, the Nuclear Regulatory Commission's (NRC) decommissioning program, or other Federal and State cleanup programs. In addition, the scope of this Guidance does not include situations involving U.S. nuclear weapons accidents."

Three federal agencies have requirements and programs specific to the cleanup and restoration of radioactive contaminated sites. Two (DOE and NRC) are developed under the authority of the AEA and the other (EPA) is under the authority of CERCLA (1980) as revised by the Superfund Amendments and Reauthorization Act of 1986. In general, all of these programs and associated standards are consistent with the DHS-recommended optimization process in that the programs have requirements to balance risks and benefits to assure that the actions taken do not cause more harm than good. The primary difference between DHS guidance and the other agency guidance is that the other agency guidance includes dose limits or risk ranges that are to be achieved if a cleanup is to be considered complete. Harmonization of the federal guidance for situations including major radiological incidents resulting in wide-area contamination will be challenging. Some key criteria under current cleanup approaches are highlighted below.

CERCLA standards are broadly applicable, covering both hazardous chemicals and radionuclides, and are also an integral part of the *National Oil and Hazardous Substances Pollution Contingency Plan* (EPA, 1990). The Plan includes a well-defined stepwise process to identify hazards, characterize the site, establish cleanup criteria, and implement the cleanup. The selection of standards for remedy and cleanup is based on three general criteria (EPA, 1990):

1. *Threshold Criteria*: Ensure overall protection of human health and the environment, and include the use of applicable or relevant and appropriate requirements. Where

these are not available or not protective, the goal is to ensure that the lifetime risk of incurring cancer from exposure to the residual contamination at a remediated site is no greater than one-in-a-million (10^{-6}) to one-in-ten-thousand (10^{-4}) (Luftig and Weinstock, 1997).

2. *Primary Balancing Criteria*: Are for long-term effectiveness, permanence, reduction in toxicity, mobility, or volume through treatment, short-term effectiveness, implementation ability, and cost.
3. *Modifying Criteria*: Include state and community acceptance of the remedy.

EPA has various tools to assist in determining Criteria 1, the Threshold Criteria, including soil screening guidance for radionuclides (Davies and Page, 2000) and radionuclide preliminary remediation goals (Davies and Page, 2002).

Looked at broadly, these criteria are similar to the optimization process with Criteria 2 including cost-benefit implications. It is important to understand that once CERCLA-related investigation and data collection are completed in the initial phases of the response, it is uncertain how the AEA material exemption applies in some scenarios. Site-specific information will be an important determinant. Should CERCLA be used for a very large radiological incident, it is likely that cost-benefit analysis will be one of the dominating factors in the remedy selection considerations, especially if public welfare needs are to be adequately addressed. For a comprehensive discussion of the details of (and similarities and differences between) EPA and NRC cleanup approaches, see NCRP Report No. 146, *Approaches to Risk Management in Remediation of Radioactively Contaminated Sites* (NCRP, 2004).

NRC standards which apply solely to radioactive material licensees approved by NRC or Agreement States are generally set forth in 10 CFR Part 20 Subpart E, *Radiological Criteria for License Termination* (NRC, 2014d). NRC (2014e) indicates a site will be considered acceptable for unrestricted use if residual activity that is distinguishable from background radiation results in a dose of <0.25 mSv y^{-1} TEDE from all pathways and has also been further reduced to levels that adhere to the ALARA principle. NRC (2014e) indicates termination for restricted use (but not termination of the institutional controls) providing it is demonstrated that further reductions to meet the unrestricted-use criteria would result in net public or environmental harm and the existing or proposed institutional controls are shown to be implementable and enforceable and provide reasonable assurance that the 0.25 mSv y^{-1} TEDE criterion will be achieved with the institutional controls (restrictions) in place. Should the institutional controls fail, it must be shown that members of the public will not be exposed to radiation that will exceed a dose criterion of 1 mSv y^{-1} TEDE in those special cases where further reduction of residual activity are not technically achievable, are prohibitively expensive, or would result in net public or environmental harm, and there are provisions for "durable institutional controls" on doses to members of the public to help keep the doses from exceeding 5 mSv y^{-1} TEDE. Durable controls include, for example, government ownership of the site.

NRC has various guides and tools to assist in implementing these requirements including NUREG-1700 Revision 1, *Standard Review Plan for Evaluating Nuclear Power Reactor License Termination Plans* (Pittiglio, 2003) which cites other guidance.

Although bounded by dose limits and dose constraints for failure of institutional controls, the NRC process is otherwise consistent with the DHS process based on the ALARA principle (*i.e.*, "optimization"). That is, consideration of modifying factors and the flexibility permitted by the restricted use alternatives in the NRC process are clearly consistent with the ALARA principle.

The DOE process is established in its recently-issued DOE Order 458.1, *Radiation Protection of the Public and Environment* (DOE, 2011). The requirements for cleanup of contaminated sites are provided in this Order. Like NRC, DOE requires that property containing residual radioactive material be remediated to a level of 0.25 mSv y^{-1} effective dose or lower by applying the ALARA principle. Clearance may be for unrestricted use or restricted use (with institutional controls). Where institutional controls are required to protect members of the public, it must be demonstrated that there is a reasonable expectation that the controls will be effective over the long term consistent with DOE Policy 454.1 (DOE, 2003). This policy delineates how DOE will use institutional controls to implement its programmatic responsibilities in the management of resources, facilities and properties under its control. Under this policy, DOE (2003) is committed to ensuring institutional controls are maintained for as long as needed.

Consistent with NRC, the DOE recommends use of similar computer codes for estimating dose to demonstrate compliance with dose limits and selecting alternative remedies through the ALARA principle. In other words, DOE requirements to apply the ALARA principle facilitate optimization.

EPA also issues cleanup (restoration) standards specific to uranium mill tailings sites in 40 CFR Part 192 (EPA, 2013b). These standards are different from the other federal standards discussed above because they apply only to contamination from mill tailings. Because the circumstances and radiological conditions at these contaminated sites are well defined, EPA applied the ALARA principle (optimization) in developing the standards and hence, established concentration limits of 0.185 Bq g^{-1} of radium for surface soil and 0.555 Bq g^{-1} of radium for subsurface soil. The requirements for remediation of structures contaminated with mill tailings are to make all reasonable efforts to reduce radon decay product concentrations to <0.02 working level (WL) (4.17×10^{-4} mJm^{-3}) in the building averaged over the year, but in any case to <0.03 WL (6.25×10^{-4} mJm^{-3}) if reasonable efforts cannot achieve 0.02 WL (4.17×10^{-4} mJm^{-3}). These optimized standards can result in individual doses ranging from a fraction of a millisievert in a year to tens of millisievert in a year, depending on occupancy and other factors. These standards have been adopted by many states for cleanup of residual radioactive material containing naturally-occurring radioactive material. DOE has also adopted them as pre-approved authorized limits for control of radium-contaminated sites in DOE Order 458.1 (DOE, 2011). But because the EPA assessment using the ALARA principle was tailored to inactive mill tailings sites, DOE requires the ALARA principle be specifically applied to their application to ensure doses adhere to the ALARA principle.

All of the above standards were reviewed by the federal interagency working group supporting the development of the DHS Planning Guidance recommendations discussed in Section 4.3.1. Although they were found to be useful benchmarks and could even be applied to some small or moderate-sized RDD situations where contamination was limited to only a building or limited area, they were not adequate to deal with the devastation and public welfare issues associated with a very large RDD or IND incident. All of the programs have been applied to the cleanup of industrial facilities and in many cases to numerous properties in the vicinity that were also contaminated by the operations at the facilities. But in all of these cases, the extent of contamination and the need for expedient response was much less than that anticipated following a large nuclear or radiological terrorist incident. For this reason, DHS Planning Guidance recommends the use of an optimization process for restoration based primarily on public welfare needs without the constraint of a predetermined dose or risk-range limit.

Abbreviations and Acronyms

AEA	Atomic Energy Act
ALARA	as low as reasonably achievable (economic and social factors being taken into account) (the ALARA principle)
ANSI	American National Standards Institute
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CGE	computable general equilibrium (model)
DNA	deoxyribonucleic acid
ERWS	En-vac® Robotic Wall Scabbler
ESF	Emergency Support Function
FRMAC	Federal Radiological Monitoring and Assessment Center
HEPA	high-efficiency particulate (a type of air filter)
HPA	Health Protection Agency (now Public Health England)
HPS	Health Physics Society
IND	improvised nuclear device
INES	International Nuclear and Radiological Event Scale
LLRW	low-level radioactive waste
LRE	Liberty RadEx (exercise)
MAUT	Multi-Attribute Utility Theory
NDRF	National Disaster Recovery Framework
NPP	nuclear power plant
NRF	National Response Framework
NUREG	U.S. Nuclear Regulatory Commission Regulation
PAG	Protective Action Guide
RCRA	Resource Conservation and Recovery Act
RDD	radiological dispersal device
RESRAD	Residual Radioactivity Computer Code
RESRAD-BUILD	Residual Radioactivity Computer Code, contaminated-building dose module

RESRAD-OFFSITE	Residual Radioactivity Computer Code, off-site contamination dose module
RESRAD-RDD	Residual Radioactivity Computer Code, radiological dispersion device dose module
SI	International System of Units
TEDE	total effective dose equivalent
TEPCO	Tokyo Electric Power Company
TMI	Three Mile Island (Nuclear Power Plant)
TNT	trinitrotoluene
TOPOFF	“top official” (exercise)
WTC	World Trade Center (New York)

Glossary

accident: An incident that has led to significant consequences to people, the environment, or the facility (IAEA, 2008).

actinide: Element with atomic number from 90 through 103; a member of the actinide series of rare earths.

action level: A level of radiation or contamination that would lead to significant radiation dose to an individual if not mitigated by engineered and/or administrative controls.

activity: The average number of spontaneous nuclear transformations occurring in a radioactive material per unit time. The unit for activity in the SI system is reciprocal second (s^{-1}) (*i.e.*, one nuclear transformation per second), with the special name becquerel (Bq). The special unit previously used was curie (Ci); $1 \text{ Ci} = 3.7 \times 10^{10}$ Bq. Activity is also expressed as disintegrations per minute per unit area (dpm cm^{-2}) with regard to surface contamination.

acute radiation exposure: Radiation exposure received during a short-time period (*e.g.*, hours).

acute radiation syndrome: A broad term used to describe a range of signs and symptoms that reflect severe damage to specific organ systems that can lead to death within hours or several weeks.

administrative control: A self-imposed, recommended control below the dose limit. If the administrative control is reached or exceeded, corrective action is initiated**.**

Agreement State: Any state with which the U.S. Nuclear Regulatory Commission has entered into an effective licensing agreement under Section 274(b) of the Atomic Energy Act of 1954, as amended, to enable the state to regulate source, special nuclear, and byproduct materials.

alpha particles: Energetic nuclei of helium atoms, consisting of two protons and two neutrons, emitted spontaneously from nuclei in the decay of some radionuclides. Alpha particles are weakly penetrating, and can be stopped by a sheet of paper or in most cases the outer dead layer of skin. Alpha particles may represent a hazard when radionuclides are deposited inside the body (*e.g.*, *via* inhalation, ingestion or wounds).

***a priori*:** Probability defined using deductive reasoning applied to the possible outcomes of a system.

aqueous: Watery; prepared with water.

as low as reasonably achievable (the ALARA principle): The principle of optimization of protection which states that the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors (ICRP, 2007).

assessment: A review, evaluation, inspection, test, check, surveillance or audit to determine and document whether items, processes, systems or services meet specific requirements and are performing effectively.

Atomic Energy Act (AEA)**:** Law passed originally in 1946 and extensively revised in 1954 that governs production and use of radioactive materials (*i.e.*, byproduct material, source material, and special nuclear material) for defense and peaceful purposes and regulation of such radioactive materials to protect public health and safety. The Act provides authority for licensing of nuclear activities by the U.S. Nuclear Regulatory Commission or Agreement States and regulation by the U.S. Department of Energy of its atomic energy defense, research and development activities.

atomic number: The number of protons in the nucleus of an atom.

attenuation: The reduction of radiation intensity *via* radioactive decay, physical dispersal of radioactive material, or shielding.

background radiation: The radiation to which a member of the population is exposed from natural sources, such as terrestrial radiation due to naturally-occurring radioactive materials in soil, cosmic radiation originating in outer space, radon, and naturally-occurring radionuclides in the human body (^{14}C, ^{40}K, and others), typically contributes an annual effective dose of 1 to 3 mSv in the United States.

becquerel (Bq)**:** The SI special name for the unit [disintegration per second (s^{-1})] of activity. 1 Bq = 1 disintegration per second; 1 Bq = 0.027×10^{-9} Ci (see *activity*).

$1 \text{ kBq} = 1 \times 10^3 \text{ Bq} = 2.7 \times 10^{-8} \text{ Ci}$
$1 \text{ MBq} = 1 \times 10^6 \text{ Bq} = 2.7 \times 10^{-5} \text{ Ci}$
$1 \text{ GBq} = 1 \times 10^9 \text{ Bq} = 2.7 \times 10^{-2} \text{ Ci}$
$1 \text{ TBq} = 1 \times 10^{12} \text{ Bq} = 2.7 \times 10^{1} \text{ Ci}$
$1 \text{ PBq} = 1 \times 10^{15} \text{ Bq} = 2.7 \times 10^{4} \text{ Ci}$

bioaccumulation: The process by which nutrients, contaminants, or other material accumulate in organisms through one or more mechanisms.

bioassay: Any procedure used to determine the nature, location or retention of radionuclides in the body by direct (*in vivo*) measurement or by indirect (*in vitro*) analysis of material excreted or otherwise removed from the body. Generally used for the purpose of estimating intake and committed dose.

biota: Plants and nonhuman animals.

buffer area or zone: Refers to adequate areas of land established to separate areas in an effective manner that otherwise could release hazardous materials from public or private lands, thus reducing risks to people in the case of contaminant releases.

buildup (of radiation in material): That part of the total value of a specified radiation quantity at any point due to radiation that has undergone interactions in the material or that results from such interactions.

byproduct material: (1) Any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure to radiation incident to the process of producing or utilizing special nuclear material; and (2) tailings or waste produced by extraction or concentration of uranium or thorium from any ore processed primarily for its source material content. Byproduct material does not include ore bodies depleted by uranium solution extraction operations and which remain underground. The Energy Policy Act of 2005 amended the definition of byproduct material to include (1) any radioactive material produced in an accelerator, (2) discrete sources of ^{226}Ra, and (3) any discrete source of naturally-occurring radioactive material, other than source material, that NRC determines would pose a threat similar to that posed by a discrete source of ^{226}Ra. NRC has not yet developed regulations to address control of these materials.

calibration: For an instrument intended to measure dose or dose-rate related quantities calibration is the determination of the instrument response in a specified radiation field delivering a known dose (rate) at the instrument location. Calibration normally involves the adjustment of instrument controls to read the desired dose (rate) and typically requires response determination on all instrument ranges. For instruments designed to measure radioactive surface contamination, calibration may be the determination of the detector reading per unit surface activity or the reading per unit radiation emission rate per unit surface area, or the reading per unit activity.

cancer: A general term for more than 100 diseases characterized by abnormal cells and altered control of proliferation of malignant cells.

catastrophic incident: Any natural or man-made incident, including terrorism, that results in extraordinary levels of mass casualties, damage, or disruption severely affecting the population, infrastructure, environment, economy, national morale, and/or government functions (FEMA, 2011a).

cement: Substance capable of making objects adhere to each other. In construction, cement is a burned and finely pulverized substance containing alumina, silica, lime, iron oxide, and magnesia that is used to form *concrete* when mixed with water, sand and aggregate.

charged particle: An atomic or subatomic quantity of matter (*e.g.*, electron, proton, alpha particle, ionized atom) having a net positive or negative electrical charge of one or more elementary units of charge.

chelate: Chemical compound in which the central atom (usually a metal ion) is attached to neighboring atoms by at least two bonds in such a way as to form a ring structure.

chelation: In chemistry, this describes the combination of a metallic ion with heterocyclic ring structures in such a way that the ion is held by bonds from each of the rings. Chelation allows removal of the bound ion from solution.

chelator: A chemical compound which causes a atom (usually a metal ion) to attach to neighboring atoms by at least two bonds in such a way as to form a ring structure. Used to remove metal atoms from aqueous media.

clay: An earthy material and component of soil that is composed mainly of fine particles of hydrous aluminum silicates and other minerals.

cleanup: Decontamination and removal of radioactive or other hazardous materials from a contaminated site. Sometimes used to refer to the more general concept of remediation.

clearance: A regulatory process to certify the removal of solid materials from an existing regulated radiation environment for the purpose of unrestricted release.

commercial waste (radioactive): Radioactive waste generated in any activity by a nongovernmental entity. Often refers to waste containing source, special nuclear, or byproduct material regulated by the U.S. Nuclear Regulatory Commission or an Agreement State, but also may refer to waste containing naturally-occurring and accelerator-produced radioactive material that is currently regulated only by the states.

committed dose equivalent: The dose equivalent averaged throughout an organ or tissue in the 50 y after intake of a radionuclide into the body (see *committed effective dose equivalent*).

committed effective dose equivalent: $H_{\mathrm{E},50}$ is the sum of the products of the committed dose equivalents for each of the body organs or tissues that are irradiated multiplied by the weighting factors (w_T) applicable to each of those organs or tissues:

$$H_{\mathrm{E},50} = \sum w_\mathrm{T} H_{\mathrm{T},50} \tag{G.1}$$

community (plant or animal): The assemblage of people that occupy a given area.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA): Law passed in 1980, and amended by Superfund Amendments and Reauthorization Act (SARA) of 1986 and later amendments, that governs federal response and compensation for unpermitted and uncontrolled releases, including threats of release, of hazardous substances, including radionuclides, to the environment. An "unpermitted" release is any release that is not properly regulated under other laws. An important focus of CERCLA/SARA is remediation of old, unpermitted waste disposal sites that are closed or inactive. Objectives of the CERCLA program are to protect human health and the environment in a cost-effective manner, maintain this protection over time, and minimize amounts of untreated waste in the environment.

concerned citizens: The term that has been used extensively in the past for these individuals is "worried well"; the Centers for Disease Control and Prevention and other federal agencies prefer to use the term *concerned citizens*. Concerned citizens may well overwhelm the capabilities of hospital emergency rooms when they do not have traumatic injuries, but are concerned because they may have been exposed to radiation or contaminated with radioactive material.

concrete: Material formed by coalescence of particles into one solid mass. In construction, concrete is a material made by mixing cement with water, sand and aggregate.

containment: Confinement of material within a designated boundary.

contamination (radioactive): Unintended and undesirable quantity of uncontained radioactive materials deposited in the environment and/or on or in persons.

cost-effectiveness: A systematic quantitative method for comparing the costs of alternative means of achieving the same stream of benefits or a given objective.

curie (Ci)**:** (see *becquerel*).

decay (radioactive): The spontaneous nuclear transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide.

decay rate: The probability that a given nucleus undergoes a spontaneous nuclear transformation in the time interval dt. The unit for decay rate is the reciprocal second (s^{-1}).

decommission: To close down a facility by reducing the residual quantities of radioactive material to a level that permits the release of the property for either limited (restricted) or unrestricted use.

decommissioning: The process of closing down a facility followed by reducing the residual quantities of radioactive material to a level that permits the release of the property for either limited (restricted) or unrestricted use.

decontaminate: To reduce or remove contaminating radioactive material from a structure, area, object or person.

decontamination: The reduction or removal of contaminating radioactive material from a structure, area, object or person.

deoxyribonucleic acid (DNA)**:** Genetic material of cells; a complex molecule of high molecular weight consisting of deoxyribose, phosphoric acid, and four bases which are arranged as two long chains that twist around each other to form a double helix joined by hydrogen bonds between the complementary components.

deposition: The process of airborne contaminants being deposited onto surfaces such as plant leaves or soil. Several processes can operate to cause deposition, including gravity, atmospheric turbulence, electrostatic attraction, rainfall.

derived concentration level guideline: A radionuclide-specific surface or volume residual activity level that is related to a concentration or dose or risk criterion.

derived intervention level: The concentration of a radionuclide in food over a selected period of time that, without any intervention, could lead to an individual receiving a radiation dose equal to a U.S. Food and Drug Administration Protective Action Guide (PAG).

detriment: Measure of stochastic effects from exposure to ionizing radiation that takes into account the probability of fatal cancers, probability of severe heritable effects in future generations, probability of nonfatal cancers weighted by the lethality fraction, and relative years of life lost per fatal health effect.

direct radiation: Radiation which reaches an observed receiving point *via* the shortest distance from its point of emission to the receiving point.

disaster: An incident that substantially disrupts and/or overwhelms normal operations.

dispersion: Spreading of a flowing substance in a medium due to random variations in the structure of the medium or random variations in the speed and direction of flow.

disposal: Placement of waste in a facility designed to isolate waste from the accessible environment without an intention to retrieve the waste, irrespective of whether such isolation permits recovery of waste.

disposal facility: Land, structures and equipment used for disposal of waste.

disposal, near-surface: Disposal of waste, with or without engineered barriers, on or below the ground surface, such that the final protective cover above the waste is on the order of a few meters thick, or in mined openings within a few tens of meters of the Earth's surface (see also *landfill*).

disposal site: Natural setting at the location of a disposal facility.

disposition: Reuse, recycling, sale, transfer, storage, treatment, consumption or disposal.

distributive fairness: Situation where individuals receive what they assume they deserve from their work or their stake.

dose: General term used to denote absorbed dose, equivalent dose, effective dose, committed effective dose equivalent, or effective dose equivalent, and to denote dose received or committed dose. Particular meaning of the term should be clear from context in which it is used (see *radiation dose*).

dose equivalent (H): The product of absorbed dose (D) at a point and the quality factor (Q) at that point for the radiation type (*i.e.*, $H = DQ$). The SI unit of dose equivalent is joule per kilogram (J kg^{-1}) with the special name sievert (Sv) (see also *effective dose equivalent*).

dose limit: A limit on dose that is applied for exposure to individuals in order to prevent the occurrence of radiation-induced deterministic effects or to limit the probability of radiation-related stochastic effects.

dose rate: Dose delivered per unit time. Can refer to any dose quantity (*e.g.*, *absorbed dose*, *dose equivalent*).

dosimeter: A radiation detection device worn or carried by an individual to monitor the individual's radiation dose.

dry deposition: The process by which atmospheric gases and particles are transferred to a surface such as vegetation or soil as a result of gravity, random turbulent air motions, diffusion, and other processes (see *deposition*).

ecological risk: The probability of harm to plants, animals or habitat in a natural or managed ecosystem from radiation or other forms of stress.

ecosystem: A system consisting of substrate (soil, sediment), nutrients, air, water, plants, and animals in a defined geographic area that functions to cycle nutrients and to pass energy captured from the sun by green plants. Ecosystems can be natural and self-sustaining, or managed to various degrees to meet human needs. Ecosystems include those in aquatic environments (freshwater, saltwater) and those in terrestrial environments. Aquatic and terrestrial ecosystems can be broken down into much more specific descriptions based on climate, soil type, vegetation type, water depth, and other parameters.

effective dose (E): The sum over specified organs and tissues (T) of the products of the equivalent dose in a tissue (H_T) and the tissue weighting factor (w_T).

$$E = \sum w_T H_T , \tag{G.2}$$

The unit for E and H_T is joule per kilogram (J kg^{-1}) with the special name sievert (Sv) (supersedes *effective dose equivalent*).

effective dose equivalent (H_E): The sum over specified organs and tissues (T) of the products of the mean dose equivalent in a tissue and tissue weighting factor (w_T).

$$H_E = \sum_T w_T H_T , \tag{G.3}$$

The unit for H_E and H_T is joule per kilogram (J kg^{-1}) with the special name sievert (Sv) (superseded by *effective dose*, but a similar formulation is used by some U.S. agencies) [see *total effective dose equivalent (TEDE)*].

effective half-life: The time in which the radionuclide within an organ decreases by one-half as a result of radioactive decay and biological elimination.

electromagnetic pulse: An abrupt burst of electromagnetic radiation usually resulting from certain types of high-energy explosions, especially a nuclear explosion, characterized by gamma rays and x rays of short wavelength and high energy; ultraviolet, visible and infrared; microwave; and radiofrequency radiation of relatively long wavelength and low energy.

emergency management: The process and institutions that are intended to respond to foreseeable disasters such that the scope and timeliness of recovery is enhanced.

environment: The collective soil, rock, water, atmosphere and biosphere making up a particular area or region.

environmental exposure: Exposure to radiation through environmental pathways.

environmental risk assessment: An evaluation intended to identify and quantitate risk to the quality and safeness of the environment for human occupancy due to a toxic agent or stressor such as radioactive material.

equivalent dose (H_T): Mean absorbed dose in a tissue or organ weighted by the radiation weighting factor. The unit of equivalent dose is joule per kilogram (J kg^{-1}) with the special name sievert (Sv) (see *effective dose* and *radiation weighting factor*).

erosion: The process of surface or near-surface soil being moved away from a given location by the action of wind or water.

evaporation: Removal of water from soil or from other materials into the atmosphere by vaporization.

exclusion zone: Area from which all employees and members of the public are excluded during scanning of conveyances. The exclusion zone is typically surrounded by radiation shielding with interlocked doors (or a fence with interlocked gates), in either case designed to maintain the effective dose rate at 0.05 μSv or less in any 1 h (above background radiation dose levels) outside the exclusion zone.

exempt: Excluded from regulation as hazardous or radioactive material.

exposure: A general term used to express the act of being exposed to ionizing radiation (also called irradiation). Exposure is also a defined ionizing radiation quantity. It is a measure of the ionization produced in air by x rays or gamma rays. The unit of exposure is coulomb per kilogram ($C\ kg^{-1}$). The special name for exposure is roentgen (R), where $1\ R = 2.58 \times 10^{-4}\ C\ kg^{-1}$.

ex situ: Moved from its original place, excavated, removed or recovered from the subsurface.

external dose: Dose to organs or tissues of an organism due to radiation sources or material located on or outside the body.

fallout: Radioactive material falling from the atmosphere to the Earth's surface after a nuclear incident, such as a weapons test, accident, or detonation of an improvised nuclear device.

family member: Any person who provides support and comfort to a patient on a regular basis and is considered by the patient as a member of their "family" whether by birth or marriage or by virtue of a close, loving relationship.

fission products: A large group of atoms, stable or unstable, produced directly or indirectly from fragments of atoms split by fission. Common examples are ^{131}I, ^{90}Sr, ^{137}Cs, and many others.

fission yield: The fraction of nuclear fissions that yield a specific fission product. Fission products with mass numbers around 90 and 140 have particularly high fission yields.

fixation: The act, process or result of becoming attached to or taken in as in soil, or as in the metabolic assimilation of atmospheric nitrogen into ammonia by soil microorganisms or the incorporation of atmospheric carbon into green plants by photosynthesis.

fuel element: A nuclear fuel component for a nuclear reactor that contains the fissile fuel matrix encapsulated in a cladding material.

gamma rays: Electromagnetic radiation (photons) emitted in nuclear transitions (*e.g.*, radioactive decay of ^{137}Cs) with energies particular to the transition. Gamma rays have high penetrating ability compared with alpha and beta particles. High-energy gamma rays are often able to penetrate deep into the body, and require thick shielding, such as up to a meter of concrete.

gray (Gy)**:** The SI special name for the unit (J kg^{-1}) of absorbed dose. 1 Gy = 1 J kg^{-1}. The conversion to the previous special unit rad is 1 Gy = 100 rad.

groundshine: The scattering of photons or neutrons from a source by the surface or volume of the ground.

groundwater: Water below the land surface in a zone of saturation that is under a pressure equal to or greater than atmospheric pressure.

half-life (radioactive): The time in which one-half of the atoms (on average) of a particular radioactive substance disintegrate into another nuclear form (also called physical or radiological half-life).

hazard: Act or phenomenon that has the potential to produce harm or other undesirable consequences to humans (*e.g.*, ionizing radiation).

hazardous waste: Waste as defined under the Resource Conservation and Recovery Act (RCRA, 1976). Under RCRA regulations, a hazardous waste is a solid waste or combination of solid waste that, because of its quantity, concentration, or physical, chemical or infectious characteristics may (1) cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness; or (2) poses a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of or otherwise managed. A solid waste is hazardous if it meets one of three conditions: (1) exhibits a characteristic of a hazardous waste [40 CFR Part 261.20 – Part 262.24 (EPA, 2013c)], (2) has been listed as hazardous [40 CFR Part 261.31 – Part 261.33 (EPA, 2013c)], (3) is a mixture containing a listed hazardous waste and a nonhazardous solid waste (unless the mixture is specifically excluded or no longer has any of the characteristics of hazardous waste).

hectacre (ha)**:** A unit of surface area; 1 ha = 10,000 m^2 = 2.47 acres.

high-level radioactive waste: (1) Highly radioactive material resulting from reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such waste that contains fission products in sufficient concentrations. (2) Other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation. In most countries other than the United States, high-level waste also includes waste from any source that contains high concentrations of shorter-lived radionuclides and high concentrations of long-lived, alpha-particle-emitting radionuclides. At the present time, however, high-level waste in the United States includes only waste produced directly in chemical reprocessing of spent nuclear fuel**.**

improvised nuclear device (IND)**:** A device designed by terrorists to produce a nuclear detonation. This includes stolen and subsequently modified nuclear weapons but does not include stockpiled weapons in the custody of the military.

incident: An event that causes consequences with a lesser scale compared to an accident. In this Report, the term *incident* generally refers to an event that is either an incident or an accident as defined by IAEA to encompass all possible incidents.

individual (personal) monitoring: The performance and interpretation of measurements by devices worn by individuals, where such measurements are generally intended to provide an estimate of the relevant dose quantity. The results of individual monitoring are mainly used to confirm the safety of working conditions, to identify unexpected exposures, and to maintain records of exposure.

ingestion: The process in which radioactive material is taken into the digestive system. The amount ingested is equivalent to an intake, although only a fraction may be absorbed into the blood system and deposited in tissues and organs and eventually excreted, mostly in urine. The ingested activity that is not absorbed to blood or in tissue or bone is excreted in feces.

in situ: Refers to being in the natural or original position or place.

institutional control: Control of a waste disposal site by an authority or institution designated under laws of a country, state or local authority. Institutional control may be active (*e.g.*, monitoring of effluents, surveillance, remedial activities, fences, or guards) or passive (*e.g.*, records or warning signs).

intake (radionuclides): (1) The process of radionuclides entering the body; or (2) the amount of radionuclides taken into the body by inhalation, absorption through the skin, ingestion, or through wounds.

***in vivo*:** From Latin "in life"; in this Report, refers to a measurement of activity inside the body *via* one or more radiological survey instruments that are external to the body.

iodide: The anionic form of iodine such as in potassium iodide.

ionizing radiation: Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions. Examples include alpha particles, beta particles, gamma rays, x rays, and cosmic rays. Minimum energy of ionizing radiation is a few electron volts (eV); $1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$.

isotope: One of several nuclides of a chemical element having the same number of protons in their nuclei, but different nuclear mass numbers due to different numbers of neutrons in the nucleus. An element may have numerous stable or unstable (radioactive) isotopes.

kiloton (kT) energy: Defined as 4.2×10^{15} J, this is approximately the amount of energy that would be released by the explosion of 1 kT (1,000 tons) of trinitrotoluene (TNT) (NCRP, 2008b) (see *TNT equivalent*).

landfill: A disposal facility or part of a facility where waste is placed in or on land and which is not a pile, a land treatment facility, a surface impoundment, an underground injection well, a salt dome formation, a salt bed formation, an underground mine, a cave, or a corrective action management unit.

leach: Dissolve soluble material by the action of percolating liquid.

leachate: The water that has been in contact with sediment or soil and whose chemical characteristics have been affected by properties of the sediment or soil, as well as the duration of contact.

leaching: The process of dissolving and moving out of a contaminant or element from a solid material such as soil by the action of a percolating liquid such as water (see *solution phase transport*).

Liberty RadEx (LRE)**:** The Liberty RadEx Exercise; an EPA conceived-and-directed drill in 2010 that tested national cleanup and recovery efforts after a simulated radiological dispersal device (RDD) attack.

ligand: In chemistry, an atom, ion or functional group that is bonded to one or more central atoms or ions, usually metals, generally through coordinate covalent bonding. An array of such ligands around a center is termed a complex.

limit: In radiation protection, the level of dose established by authoritative or consensus bodies above which the consequences to an individual would be regarded as unacceptable.

low-level radioactive waste (LLRW)**:** Radioactive waste that (A) is not high-level radioactive waste, spent nuclear fuel, transuranic waste, or byproduct material as defined in Section 11(e)(2) of the Atomic Energy Act, and (B) the U.S. Nuclear Regulatory Commission, consistent with existing law, classifies as LLRW. Byproduct material referred to in Clause A essentially is uranium or thorium mill tailings. LLRW does not include waste containing naturally-occurring and accelerator-produced radioactive material, although such waste may be managed as LLRW. In most countries other than the United States, LLRW includes only radioactive waste that contains the lowest concentrations of radionuclides, but LLRW in the United States can contain high concentrations of shorter-lived radionuclides and high concentrations of long-lived radionuclides other than long-lived, alpha-particle-emitting transuranium radionuclides.

Low-Level Radioactive Waste Policy Amendments Act (LLRWPAA)**:** Law passed in 1980 and amended in 1985 that governs disposal of low-level radioactive waste by states or State Compacts. The Act does not govern disposal of LLRW generated at U.S. Department of Energy sites unless such waste is sent to a disposal facility established under the Act. All waste disposals under the Act will be licensed by the U.S. Nuclear Regulatory Commission or an Agreement State.

marine: Refers to saltwater habitat such as oceans, seas and estuaries.

members of the public: All persons who are not considered occupationally exposed by a source or practice under consideration.

mitigation: Reduction of or neutralizing the effects of a disaster.

mixed waste: Waste containing radionuclides (*i.e.*, source, special nuclear, or byproduct materials), as defined in the Atomic Energy Act, and hazardous chemical waste regulated under the Resource Conservation and Recovery Act (RCRA, 1976). Mixed waste also may include (1) waste containing radionuclides as defined in the Atomic Energy Act and hazardous chemical waste regulated under the Toxic Substances Control Act (TSCA, 1976) and (2) waste containing naturally-occurring and accelerator-produced radioactive material and hazardous chemical waste regulated under RCRA or TSCA.

mobility: The capability of moving or being moved.

model: A mathematical or physical representation of an environmental or biological system, sometimes including specific numerical values for parameters of the system.

monitoring: (1) Periodic or continuous estimation of the exposure rate in an area (area monitoring) or the exposure received by a person (individual or personal monitoring). (2) The use of portable survey meters to determine the presence or quantity of radioactive contamination on an individual, or the use of a dosimeter (*i.e.*, a small portable measurement and recording device) to determine an individual's radiation dose or intake of activity. (3) The routine and normally repeated measurement of radiation levels or quantities of radionuclides in environmental media such as air, water, soil, vegetation, fish and milk.

municipal/industrial landfill: A facility for disposal of solid waste that meets the regulatory criteria established under Subtitle D of the Resource Conservation and Recovery Act (RCRA, 1976) or is otherwise acceptable for disposal of nonhazardous waste.

nationally-significant incident: An incident for which response exceeds regional resources.

naturally-occurring radioactive material: Any radioactive material that is naturally occurring and that is not source, special nuclear, or byproduct material.

new normality: A state of existence different from the previous state of normalcy.

nuclear fuel cycle: Normal life cycle of uranium used as fuel in nuclear reactors including: mining of uranium ore; milling of uranium ore to produce U_3O_8 concentrate; refining of that concentrate to remove impurities; chemical conversion of that concentrate to UF_6; enrichment of the ^{235}U content by gaseous diffusion; fabrication of nuclear fuel (usually by chemical conversion to UO_2 and sintering into fuel rods); burning of fuel in a nuclear reactor for electricity generation, defense plutonium production, production of other isotopes, or research and development; chemical reprocessing of spent nuclear fuel to recover the remaining uranium and plutonium (commercial spent nuclear fuel is not currently reprocessed); consolidation of spent nuclear fuel rods or encapsulation of liquid reprocessing waste in borosilicate glass or other suitable waste form preparatory to disposal; and storage and disposal of spent nuclear fuel and solidified reprocessing waste.

nuclear incident: Pertains to an improvised nuclear device (IND) or other type of nuclear detonation.

nuclear yield: The amount of energy that is released when a nuclear weapon is detonated, expressed usually as the equivalent mass of trinitrotoluene (TNT) [*e.g.*, in kilotons (thousands of tons of TNT)].

nuclide: Species of atoms having a specified number of protons and neutrons in its nucleus. Unstable nuclides that transform to stable or unstable progeny and release radiation are called radionuclides.

optimization (of radiation protection): [see *as low as reasonably achievable (the ALARA principle)*].

pathway: Route of entry of radionuclides into the body.

person-sievert (person-Sv**):** The unit of collective *effective dose*.

pH: A measure of acidity and alkalinity of a solution that is a number on a scale on which a value of seven represents neutrality, lower numbers indicate increasing acidity, and higher numbers increasing alkalinity.

pollutant: Includes, but is not limited to, any chemical element, substance, compound or mixture, including disease-causing substances, which after release into the environment and upon external exposure, ingestion, inhalation or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will, or may reasonably be anticipated to, cause death, disease, behavioral abnormalities, cancer, genetic mutation, or physiological malfunctions (including malfunctions in reproduction, or physical deformations in such organisms or their offspring).

program: The integration of a set of processes and other activities that are planned, initiated and managed in a coordinated way to achieve desired results.

Protective Action Guide (PAG): A radiation dose guideline or level at which protective action such as evacuation or staying indoors should be considered to limit the radiation dose to members of the public.

rad: (see *gray*).

radiation (ionizing): Electromagnetic radiation (x rays or gamma rays) or particulate radiation (alpha particles, beta particles, electrons, positrons, protons, neutrons, and heavy-charged particles) capable of producing ions by direct or secondary processes in passage through matter.

radiation dose (or dose): A general term used when the context is not specific to a particular radiation dose quantity. When the context is specific, the name for the quantity is used (*e.g.*, *absorbed dose*, *equivalent dose*, *effective dose*).

radiation units and names: (see *becquerel*, *gray* and *sievert*).

radiation weighting factor (w_R): A factor used to allow for differences in the biological effectiveness between different radiations when calculating equivalent dose (H_T). These factors are independent of the tissue or organ irradiated.

radioactive contamination: Unintended and undesirable quantity of uncontained radioactive materials deposited in the environment and/or on or in persons [see *contamination (radioactive)*].

radioactive decay: The spontaneous transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide. The process results in an exponential decrease, with time, of the number of the radioactive atoms in a sample at a rate controlled by its half-life.

radioactive waste: Solid, liquid or gaseous materials of no value that contain radionuclides, either man-made or naturally occurring, and are regulated as hazardous material due to the presence of radionuclides.

radioactivity: Property or characteristic of an unstable atomic nucleus to spontaneously transform with emission of energy in the form of ionizing radiation.

radioiodine: A radioisotope of iodine (*e.g.*, ^{131}I).

radioisotope: A radioactive atomic species of an element with the same atomic number and usually identical chemical properties.

radiological: A general term pertaining to radiation and radioactive material.

radiological dispersal device (RDD**):** A device designed to spread radioactive material through a detonation of conventional explosive or other (non-nuclear) means.

radiological incident: Pertains to dispersal of one or more radionuclides.

radionuclide: An unstable (radioactive) nuclide. A species of atom characterized by the constitution of its nucleus (*i.e.*, the number of protons and neutrons) and the excess energy available in the unstable nucleus.

recommendation: Suggestion that, when implemented, could improve the performance and effectiveness of a task, process or program.

recovery: The process of restoring to the former normality or to a "new normal" as circumstances may warrant.

reference level: In emergency or existing controllable exposure situations, this represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimization of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration (ICRP, 2007).

rem: (see *sievert*).

remediate: To take action to reduce risks to human health or the environment posed by the presence of radioactive or hazardous chemical contaminants at a site including, but not restricted to, excavation of contaminated soil, removal of contaminants from building surfaces or equipment, stabilization of buried waste, and installation of engineered barriers (*e.g.*, caps on waste trenches) to reduce the potential for migration of contaminants.

remediation: Actions taken to reduce risks to human health posed by the presence of radionuclides.

residual (contamination or dose): Radioactive material in structures, materials, soils, groundwater, and other media at a site resulting from activities under the site operator's control, especially radioactive material remaining at a site after decommissioning and remediation. Residual radioactive material does not include naturally-occurring radioactive material in its undisturbed state.

resilience: The capacity of a system to absorb disturbance, undergo change, and retain the same essential functions, structure, identity, and feedbacks (Longstaff *et al.*, 2010.

Resource Conservation and Recovery Act (RCRA**):** Law passed in 1976 as amendment to Solid Waste Disposal Act of 1965 (SWDA, 1965), and amended in 1980 and again in 1984 by Hazardous and Solid Waste Amendments (HSWA, 1984), that governs generation, transport, treatment, storage and disposal of solid hazardous waste and disposal of nonhazardous solid waste in municipal/industrial landfills. Solid hazardous waste regulated under RCRA are defined in

40 CFR Part 261 (EPA, 2013c), Subpart A, and specifically exclude source, special nuclear, and byproduct materials as defined in the Atomic Energy Act (AEA, 1954). Objectives of RCRA include protection of human health and the environment, expeditious reduction or elimination of generation of hazardous waste, and conservation of energy and natural resources (*i.e.*, material recycling and recovery).

response: Manner with which entities, institutions and people react to an emergency or a disaster.

restoration: The return of a contaminated area, ecosystem, buildings, and/or infrastructure to their previous noncontaminated state.

resuspension: Transfer of material that has been deposited on the ground surface to the atmosphere through some form of disturbance, such as wind; also commonly used to mean suspension for material on the ground surface that was not deposited from the atmosphere. These terms can also apply to suspension or resuspension of sediments into the water column of an aquatic system.

retention: Describes the propensity for radioactive materials to remain at the site of deposition on or within the body. As used in mathematical models, retention is quantitatively expressed by such parameters as biological half-times or rate constants pertaining to specific loss processes from an organism or from a specific compartment such as an organ or other component of the ecosystem. High retention implies a low clearance rate.

risk: The probability of a specified effect or response occurring.

absolute risk: Expression of excess risk due to exposure as the arithmetic difference between the risk among those exposed and that obtaining in the absence of exposure.

annual risk: The risk in a given year from an earlier exposure. The annual risk (average) from an exposure is the lifetime risk divided by the number of years of expression.

lifetime risk: The total risk in a lifetime resulting from exposure(s). It is equal to the average annual risk times the period of expression.

relative risk: An expression of excess risk relative to the underlying (baseline) risk; if the excess equals the baseline risk the relative risk is two.

risk assessment: Analysis of potential adverse impacts of an incident (*e.g.*, radioactive waste disposal) upon the well-being of an individual or a population (referring to humans or other organisms). Risk assessment is a process by which information or experience concerning causes and effects under a given set of circumstances is integrated with the extent of those circumstances to quantify or otherwise describe risk. Often, risk assessment for radionuclides in the environment involves estimation of concentrations in environmental media, human exposure to that media, radiation dose resulting from the exposure, and the calculation of health risk resulting from the estimated dose.

risk characterization: An integration and interpretation of the information developed during hazard identification, dose-response assessment, and exposure assessment to yield an estimate of risk to human health or other organisms, including an identification of limitations and uncertainties in models and data. Risk characterization is the final step of a risk assessment.

runoff: The process of water running off the land surface rather than infiltrating the soil.

Safe Drinking Water Act: Law passed in 1974 and amended several times since, most recently by the Safe Drinking Water Act Amendments of 1996 that addresses protection of the nation's drinking water supplies and resources. The Act provides authority for National Primary Drinking Water Regulations for hazardous contaminants in drinking water, including radionuclides, and national requirements for State Underground Injection Control programs.

scenario: Set of assumptions about the future behavior of a disposal system, past exposures of individuals, or future exposures of individuals.

screening: Process of rapidly identifying potentially-important radionuclides or release, transport or exposure pathways by eliminating those of known lesser significance. Also used to describe, using simplified bounding calculations, the upper limit of exposure, dose or risk.

screening-level models: Simple models employing conservative assumptions for the expressed purpose of eliminating radionuclides and pathways of negligible importance.

sediment: The solid matter, organic and/or inorganic, that settles to the bottom of a water body; material deposited by water, wind or glaciers.

sedimentation: The process of sediment deposition and accumulation on the bottom of a body of water.

sievert (Sv)**:** The SI special name for the unit (J kg^{-1}) of dose equivalent, effective dose, effective dose equivalent, equivalent dose, and total effective dose equivalent (TEDE). 1 Sv = 1 J kg^{-1}. The conversion to the previous special unit rem is 1 Sv = 100 rem.

SI units: The International System of Units as defined by the General Conference of Weights and Measures in 1960. These units are generally based on the meter/kilogram/second units, with special quantities for radiation including the *becquerel*, *gray* and *sievert*.

slag: Carbonate and nonmetallic oxide compounds produced by the chemical reaction of flux and impurities in a steelmaking furnace. Iron and steelmaking slags tend to be rock-like when they cool and harden.

solid waste: Material regulated under the Resource Conservation and Recovery Act (RCRA. 1976) and defined in 40 CFR Part 261.2 and Part 261.4 (EPA, 2013c). Solid waste includes, but is not restricted to, material that has been discarded, abandoned, or is inherently waste-like, and such waste can be a solid, liquid or gas.

sorb: The attachment of some material of interest to a solid surface by one of several possible mechanisms.

special nuclear material: Defined by Title I of the Atomic Energy Act of 1954 (AEA, 1954) as plutonium, ^{233}U, or uranium enriched in the isotopes ^{233}U or ^{235}U. The definition includes any other fissile material that the U.S. Nuclear Regulatory Commission (NRC) determines to be special nuclear material, but does not include source material. NRC has not declared any other material as special nuclear material.

spent nuclear fuel: Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

stakeholder: A person, group or organization having interest in or potential to be affected by an organization.

standards: A variety of activities established by legislative, regulatory or consensus means for the safe use and application of ionizing and nonionizing radiation. Examples include: dose and dose rate limits, permissible concentrations, rules for handling, regulations for transportation, regulations for industrial control of radiation, electronic product performance requirements, and control of radioactive material and recommended practice documents (*e.g.*, NCRP reports, American National Standards, good practice documents).

suspension: Transfer of material from the Earth's surface, including surface water and the land surface, to the atmosphere.

tissue weighting factor (w_T): A factor that indicates the ratio of the risk of stochastic effects attributable to irradiation of a given organ or tissue (T) to the total risk when the whole body is uniformly irradiated. When calculating effective dose equivalent, the tissue weighting factor represents the risk of fatal cancers or severe heritable effects. When calculating effective dose, tissue weighting factor represents total detriment.

TNT equivalent: A measure of the energy released in the detonation of a nuclear (or atomic) weapon, or in the explosion of a given quantity of fissionable material, expressed in terms of the mass of TNT which would release the same amount of energy when exploded. The TNT equivalent is usually stated in kilotons or megatons. The basis of the TNT equivalence is that the explosion of one ton of TNT is assumed to release 10^9 calories of energy).

TOPOFF: A series of national-level, chemical/biological/radiological/nuclear exercises designed for federal, state, territorial and local top officials and other responders.

total effective dose equivalent (TEDE)**:** The sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (from intakes of radionuclides) (NRC, 2014a). TEDE accumulates over a period of time that includes external irradiation as well as committed doses due to radionuclide intakes during that period of time.

toxic: (1) Capable of producing injury, illness or damage to living organisms through ingestion, inhalation or absorption through any body surface. (2) A characteristic of solid hazardous waste regulated under the Resource Conservation and Recovery Act (RCRA, 1976) and defined in 40 CFR Part 261.24 (EPA, 2013c). A solid waste is toxic if, when using the Toxicity Characteristic Leaching Procedure, the extract from a representative sample of the waste contains any of 40 contaminants (seven metals and 33 organic compounds) at a concentration equal to or greater than specified values. When the waste contains <0.5 % filterable solids, the waste itself, after filtering, is considered to be the extract for the purpose of determining whether it is toxic.

uptake: Refers to the process of radionuclide transport from the environment into biological tissues (*e.g.*, soil to plants, water to fish). In the medical use of radionuclides, uptake refers to the accumulation of administered activity to a particular organ or tissue at a particular time after administration.

uranium: A naturally-radioactive element. In natural ores, it consists of 0.7 % ^{235}U, 99.3 % ^{238}U, and a small amount of ^{234}U.

verification: Determination that a computer (or any other) implementation of a mathematical equation or set of equations is without significant error.

waste classification: (1) System for classifying waste arising from operations of nuclear fuel cycle including spent nuclear fuel (if it is declared to be waste), high-level waste, transuranic waste, low-level radioactive waste, and uranium or thorium mill tailings; or (2) system for classifying radioactive waste that is generally acceptable for near-surface disposal developed by U.S. Nuclear Regulatory Commission (NRC, 2013a).

waste management: Activities associated with disposition of waste products after their generation, including treatment, storage, transportation and disposal, as well as actions to minimize production of waste.

waste minimization: The reduction, to the maximum extent feasible, of waste volume that is generated or subsequently treated, stored or disposed of. It includes any source reduction or recycling activity undertaken by a generator that results in either (1) the reduction of total volume or quantity of waste, or (2) the reduction of the toxicity of the waste, or (3) both, so long as such reduction is consistent with the goal of minimizing present and future threats to human health and the environment.

weathering: The process of loss of a contaminant from plant or other types of surfaces by actions of wind, rain, or other disturbance. The time required for half the material deposited onto surfaces of vegetation from the atmosphere to be lost is referred to as the weathering half-time. This term is also used to describe the process of mineral aging (*i.e.*, the weathering of mica to form other minerals such as illite).

x rays: Penetrating electromagnetic radiation having a range of wavelengths (energies) that are similar to those of gamma rays. X rays are usually produced by interaction of the electron field around certain nuclei or by the slowing down of energetic electrons. Once formed, there is no physical difference between gamma rays and x rays; however, there is a difference in their origin.

zeolite: Any of a number of hydrous silicates of aluminum, sodium or calcium found in cavities of igneous rocks. It is sometimes used to adsorb radionuclides from solution.

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Scientific Committee and Staff

S.Y. Chen (*Chairman*) is currently Director of Professional Master of Health Physic Program at the Illinois Institute of Technology (IIT), Chicago. Prior to joining IIT, he was Senior Environmental Systems Engineer and also served as the Strategic Area Manager in Risk and Waste Management in the Environmental Science Division at Argonne National Laboratory, Argonne, Illinois. He received his BS in nuclear engineering from National Tsing Hua University in Taiwan and obtained his MS and PhD in nuclear engineering from the University of Illinois at Champaign-Urbana. Dr. Chen's professional interests include radiation protection, human and environmental health risk, and nuclear accident analysis; with special expertise in environmental cleanup, radioactive material disposition management, and nuclear waste transportation. Dr. Chen has been a NCRP Council member since 1999, and served on its Board (2004 to 2011). He currently serves as NCRP Scientific Vice President on Environmental Radiation and Waste Issues (since 2004). Dr. Chen has served on the U.S. Environmental Protection Agency's Science Advisory Board/Radiation Advisory Committee since 2009. He is a long-time member of the Health Physics Society and of the American Nuclear Society. He was elected to Fellow by the Health Physics Society in 2013, and is a Certified Health Physicist by the American Board of Health Physics. While at Argonne, Dr. Chen developed an integrated risk assessment program that addresses the broad-based issues to support federal risk-based policies. Dr. Chen had served on numerous capacities at NCRP, including chairing Scientific Committee (SC) 87-4 which led to the publication of Report No. 141, *Managing Potentially Radioactive Scarp Metal*, and also chairing SC 5-1, *Decision Making for Late-Phase Recovery from Major Nuclear or Radiological Incidents*. He served as Chair of NCRP 2005 Annual Meeting Program Committee, Managing the Disposition of Low-Activity Radioactive Materials, and as Co-Chair of NCRP 2013 Annual Meeting Program Committee, *Radiation Dose and the Impacts on Exposed Populations*.

Daniel J. Barnett is an Assistant Professor in the Department of Environmental Health Sciences at the Johns Hopkins Bloomberg School of Public Health. He has a Joint Faculty appointment in the Department of Health Policy and Management at the school. He is affiliated with the Centers for Disease Control and Prevention funded Johns Hopkins Center for Public Health Preparedness. His research interests include best practice models to enhance all-hazards public health emergency preparedness and response, with a strong interest in preparedness for radiological and nuclear terrorism threats. Specific areas of focus include willingness of health providers to respond to public health emergencies, risk communication; personal and family emergency preparedness planning, vulnerable populations in emergencies, and psychosocial impacts of disasters. He received a BA in English from Yale University, and his MD degree at the Ohio State University College of Medicine and Public Health; his MPH degree was earned at the Johns Hopkins Bloomberg School of Public Health and he is a graduate of the Johns Hopkins General Preventive Medicine Residency Program.

Brooke R. Buddemeier is an associate program leader in the Global Security Directorate of Lawrence Livermore National Laboratory (LLNL). He supports the Risk and Consequence Management Division in their efforts to evaluate the potential risk and consequence of radiological and nuclear terrorism. Mr. Buddemeier is a member of NCRP and served on the scientific committees which developed Commentary No. 19, *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism* (2005) and NCRP Report No. 165, *Responding to a Radiological or Nuclear Terrorism Incident: A Guide for Decision Makers* (2010). From 2003 through 2007, he was on assignment with the Department of Homeland Security's as the weapons of mass destruction emergency response and consequence management program manager for Science and Technology's emergency preparedness and response portfolio. He supported Federal Emergency Management Agency and the Homeland Security Operations Center as a radiological emergency response subject matter expert. He also facilitated the department's research, development, test and evaluation process to improve emergency response through better capabilities, protocols and standards. Prior to that, he was part of the LLNL Nuclear Counterterrorism Program and coordinated LLNL's involvement in the National Nuclear Security Administration's Radiological Assistance Program (RAP) for California, Nevada and Hawaii. RAP is a national emergency response resource that assists federal, state and local authorities in the event of a radiological incident. As part of RAP's outreach efforts, Mr. Buddemeier has provided radiological responder training and instrumentation workshops to police, firefighters, and members of other agencies throughout the nation and abroad. He has also provided operational health physics support for various radiochemistry, plutonium handling, accelerator and dosimetry operations. He is Certified Health Physicist who received his Master's in Radiological Health Physics from San Jose State University and a BS in Nuclear Engineering from the University of California, Santa Barbara.

Vincent T. Covello is the Director of the Center for Risk Communication in New York City. He is an expert in risk and crisis communications and has conducted trainings and consulted for several hundred organizations. Dr. Covello's assignments include trainings, workshops and consultations related to a wide range of high-concern or high-stress issues, including communications about air pollution, water contamination, product safety, mining accidents, industrial accidents, chemical safety, worker safety, food safety, hazardous waste, radiation, terrorism, organizational change, earthquakes, hurricanes, tornadoes, climate change, oil spills, and chemical spills.

Over the past 30 y, Dr. Covello has held positions in academia and government. Prior to establishing the Center for Risk Communication, he was Associate Professor of Environmental Sciences and Clinical Medicine at Columbia University (1988 to1992).
Dr. Covello also serves as an advisor to the World Health Organization and many other national and international agencies.

Dr. Covello is the Past President of the Society for Risk Analysis, a professional association with over 3,000 members. Dr. Covello received his doctorate from Columbia University in 1976 and his bachelors with honors and masters degrees from Cambridge University in England.

Dr. Covello has authored or edited more than 25 books and over 150 published scientific articles on risk and crisis communications. In 2007, Dr. Covello co-authored *Effective Media Communication During Public Health Emergencies: A World Health Organization Handbook*. This handbook is currently being used by agencies and organizations around the world to communicate effectively with the media and other key audiences about pandemic influenza and the H1N1 (swine flu) outbreak. In 2011, following the nuclear power plant accident in Japan, Dr. Covello wrote two comprehensive guidance documents at the request of the U.S. Nuclear Regulatory Commission for the nuclear power industry: G*uidance on Developing Effective Radiological Risk Communication Messages*, and *Developing an Emergency Risk Communication / Joint Information Center Plan for a Radiological Emergency.*

Katherine Kiel is a Professor of Economics at the College of the Holy Cross in Worcester, Massachusetts. Her research is on real estate price indices, racial discrimination in housing markets, and the demand for environmental quality in the United States. Her work has been published in journals such as *Land Economics* and the *Journal of Urban Economics.* She is currently a board member for the New England Economic Partnership and is on the Board of Economic Advisors for Associated Industries of Massachusetts. In the past she served on the U.S. Environmental Protection Agency's Advisory Council on Clean Air Compliance. She received her PhD in Economics from the University of California at San Diego and her AB from Occidental College.

Jill A. Lipoti was the Director of Water Monitoring and Standards at the New Jersey Department of Environmental Protection until her retirement in 2013. From 1989 to 2010, she directed the activities of the Radiation Protection Programs for New Jersey, with responsibility for the x ray, radioactive materials, nuclear emergency response, environmental monitoring, radon, and non-ionizing programs, involving regulation and licensure of professionals. She received the Edward J. Ill Excellence in Medicine Award in 2009 for her work in reducing patient radiation dose from x rays. Dr. Lipoti served as the New Jersey Commissioner to the Atlantic Interstate Low-Level Radioactive Waste Compact. Dr. Lipoti was elected to the Board of Directors and as Chairperson for the Conference of Radiation Control Program Directors (CRCPD), a nonprofit organization representing all 50 states. In

2000, she received the Gerald S. Parker Award of Merit, the CRCPD's highest award. Dr. Lipoti was elected to NCRP in 2001 and has served on the Board of Directors, Program Area Committee 5 on Environmental Radiation and Radioactive Waste Issues, and on Scientific Committee 5-1, Approach to Optimizing Decision Making for Late-Phase Recovery From Nuclear or Radiological Terrorism Incidents. She served as a member and chair of the Radiation Advisory Committee of the Environmental Protection Agency's Science Advisory Board (SAB) and also served on the SAB's Committee on Science Integration for Decision Making. She served on the Food and Drug Administration's Technical Electronic Product Radiation Safety Standards Committee. Dr. Lipoti served on the National Academies committee to write a report on Uranium Mining in Virginia under the Board on Earth Sciences and Resources. Dr. Lipoti received the Distinguished Alumni George H. Cook Award, Cook College, Rutgers University. She received her PhD in Environmental Science from Rutgers University in 1985. She has traveled to Uganda and Ethiopia on missions for the International Atomic Energy Agency.

Debra McBaugh Scroggs is a Senior Health Physicist [radiation protection scientist] with Dade Moeller & Associates. A Certified Health Physicist, Ms. McBaugh Scroggs has more than 30 y of experience in the radiation protection field. Prior to Dade Moeller & Associates, at the Washington State Department of Health, Radioactive Materials Section, she led a staff of 10 in inspecting and licensing facilities that receive, possess, use, transfer, or acquire radioactive materials. She also managed investigations of incidents involving radioactive materials and participated in emergency response drills and exercises. Earlier she managed the State's Environmental Radiation Section, which was responsible for the environmental monitoring and assessment of nuclear facilities such as the U.S. Department of Energy's Hanford Site. During this time, Ms. McBaugh Scroggs also was appointed to the U.S. Commission on Fire Safety and Preparedness for the U.S. Department of Energy and chaired its Subcommittee on Environmental, Fire Risk Management, and Community Involvement.

Ms. McBaugh Scroggs is a member of the Board of Directors of NCRP and is a member of the Health Physics Society's Homeland Security Committee. Previously, she served Chair of the Conference of Radiation Control Program Directors (CRCPD) (2005 to 2007). She was Chair of CRCPD's Decommissioning Committee (1996 to 2001). She is also an active member of the Health Physics Society, serving the national organization as a member of the Strategic Planning Committee (2003 to 2005), President of the Decommissioning Section (2003 and 2004), and Co-Chair of the Society's 1996 Annual Meeting in Seattle.

A lifelong resident of Washington, she earned both her BS in Physics and her MS in Radiological Sciences from the University of Washington in Seattle.

Andrew Wallo, III, is a health and environmental physicist with expertise in public and environmental radiation protection, radioactive waste management, emergency response, and radiation protection policy. He has a BS in physics from Wilkes University and an MS in radiation science from Georgetown University. He has been a member of the Health Physics Society for 29 y and has served as a member or consultant to a number of NCRP, American National Standards Institute, and International Atomic Energy Agency working groups and committees covering radioactive waste, waste security, and residual radioactive material control.

He is currently with the U.S. Department of Energy (DOE) and is the Deputy Director of the Office of Environmental Protection, Sustainability Support, and Corporate Safety Analysis within the Office of Health, Safety, and Security. In this position he is responsible for developing agency radiation and environmental protection policy and requirements, and for supporting analyses and programs to improve worker and public safety and the environment. He previously served as Deputy Director in the Office of Nuclear Safety, Quality Assurance and Environment where responsibilities included development of DOE nuclear safety, quality assurance, and environmental protection requirements and expectations.

Responsibilities also included the DOE lead for coordinating on environmental protection issues including work with other agencies on the development of protective action guidance for radiological emergencies, and federal radiation protection guidance. He is the DOE representative to the Interagency Steering Committee on Radiation Standards. Mr. Wallo also serves as the a representative to the DOE Federal Low Level Waste Review Group. Prior to joining DOE, Mr. Wallo was employed by the Aerospace Corporation and the MITRE Corporate working in a variety of areas related to radiation protection and environmental measurement, monitoring and control.

David J. Allard (*Advisor*) is the Director of Pennsylvania's Department of Environment Protection (DEP) Bureau of Radiation Protection; responsible for the accelerator, x ray, environmental surveillance, nuclear safety, radiological emergency response, radioactive materials, decommissioning/site cleanup, low-level waste and radon programs within the Commonwealth. He is the Governor's official liaison to the U.S. Nuclear Regulatory Commission, and a Commissioner for the Appalachian States Low-Level Radioactive Waste Compact Commission.

Mr. Allard received a BS in Environmental Sciences from the State University of New York - Albany and an MS in Radiological Sciences and Protection from the University of Massachusetts - Lowell. He is certified by the American Board of Health Physics, a Fellow of the Health Physics Society, and the Conference of Radiation Control Program Directors' official liaison to NCRP.

Prior to joining DEP in February 1999, he was a consultant to the U.S. Department of Energy on environmental and occupational radiation protection for 8 y. Mr. Allard has been involved in the various aspects of governmental, industrial, reactor, medical and academic radiation protection for 36 y. He serves as a member or advisor on several national radiation protection committees, has authored numerous professional papers and reports, and lectures frequently on a wide variety of radiation protection topics and concerns.

Jonathan D. Edwards (*Advisor*) became Director of the U.S. Environmental Protection Agency's (EPA) Radiation Protection Division in December of 2008. The Division is located in the Office of Air and Radiation and is responsible for working to protect human health and the environment from unnecessary exposure to radiation. As Division Director, Jon is responsible for several programs including EPA's radiological emergency response program, environmental oversight of the U.S. Department of Energy's (DOE) deep geological repository known as the Waste Isolation Pilot Plant near Carlsbad, New Mexico; scientific and technical radiation risk assessments; and other radiation protection activities and programs.

Mr. Edwards graduated from the U.S. Naval Academy in Annapolis, Maryland, in 1985 and completed 2 y of post-graduate nuclear engineering instruction and training and was awarded the designation of "Nuclear Ship Engineer Qualified," by the Naval Sea Systems Command and DOE. He served out of Norfolk, Virginia, on the fast attack submarine USS SPADEFISH (SSN-668) as Main Propulsion Assistant and Assistant Engineer.

Upon leaving the Navy in 1993, Jon began work with EPA as a health physicist in the radiation program. He was closely involved with protective action guidance training, exercise development and execution, and providing technical advice as needed for emergency guidance/policy development. Specifically, Mr. Edwards was selected as part of the multi-federal agency force that provided counterterrorism support in Atlanta during the summer Olympic Games of 1996. Jon spent the years of 1997 through 1999 working as a special assistant to the Assistant Administrator for Air and Radiation and as a senior planner/policy advisor in the EPA Office of Research and Development's Office of Science Policy.

In late 1999, Mr. Edwards returned to the EPA radiation program as the Director of the Center for Radiation Information and then, following the attacks of September 2001, as the Director of EPA's radiation emergency program. In early 2003, at about the time of the creation of the U.S. Department of Homeland Security, then-EPA Administrator Christy Todd Whitman approved Jon's reassignment to Deputy Director of EPA's Office of Homeland Security (OHS), a new policy office formed to advise the EPA Administrator on homeland security issues. Jon served a number of years with OHS, garnering wide respect for his agency-wide leadership on initial EPA homeland security policies and strategies. Jon served with OHS until his current assignment as Director, Radiation Protection Division.

Helen A. Grogan (*Advisor*) is President of Cascade Scientific, Inc., an environmental consulting firm. Dr. Grogan received her PhD from Imperial College of Science and Technology at the University of London in 1984 and has more than 25 y of experience in radioecology, environmental dose reconstruction, and the assessment of radioactive and nonradioactive hazardous waste. She first worked at the Paul Scherrer Institute in Switzerland on the performance assessment of radioactive waste disposal for the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra). Dr. Grogan was actively involved in the early international cooperative efforts to test models designed to quantify the transfer and accumulation of radionuclides and other trace substances in the environment. Validation of computer models developed to predict the fate and transport of radionuclides in the environment remains a key interest of hers. In 1989 Dr. Grogan returned to the United Kingdom as a senior consultant to Intera Information Technologies before moving to the United States a few years later, where she has worked closely with Risk Assessment Corporation managing the technical aspects of a wide variety of projects that tend to focus on public health risk from environmental exposure to chemicals and radionuclides. Dr. Grogan has served on committees for the National Academy of Sciences, the International Atomic Energy Agency, the U.S. Environment Protection Agency, and NCRP. She co-edited the text book *Radiological Risk Assessment and Environmental Analysis* published by Oxford University Press in July 2008, and authored the chapter on Model Validation.

Anne F. Nisbet (*Advisor*) has more than 25 y experience in radiation protection, specializing in radioecology, emergency planning and response, recovery and rehabilitation strategies, and stakeholder engagement processes. She works for Public Health England and previously for one of its predecessor organizations, the National Radiological Protection Board. Dr. Nisbet currently has responsibility for updating and consolidating emergency and recovery protection advice for radiation incidents in the United Kingdom. She is a member of the International Commission on Radiological Protection (ICRP) Committee 4 and served on the Task Group responsible for ICRP Publication 111, which provided guidance for the protection of people living in long-term contaminated areas after a nuclear accident. Dr. Nisbet is currently a consultant to the International Atomic Energy Agency in the area of recovery and remediation. She was also involved in an International Radiological Protection Association Task Group that published guiding principles for stakeholder engagement. In 2010 Dr. Nisbet participated as an international expert in Exercise Liberty RadEx in Philadelphia and was subsequently asked to join a NCRP scientific committee to work on decision making for late-phase recovery from nuclear or radiological incidents. She is the lead author of the U.K. Recovery Handbook for Radiation Incidents and also its European counterpart. She has coordinated various European research projects (e.g., EURANOS) and a European stakeholder network (FARMING). Dr. Nisbet was awarded her PhD in Geochemistry from Imperial College London in 1984. She is a Chartered Radiation Protection Professional.

John J. Cardarelli (*Consultant*) received a BS in Nuclear Engineering (1990), an MS in Health Physics (1992), and PhD in Industrial Hygiene (2000) from the University of Cincinnati. He holds a Professional Engineering License (nuclear specialty), and is board certified in both Industrial Hygiene and Health Physics. From 1992 until 2005, he worked for the Centers for Disease Control and Prevention at the National Institute for Occupational Safety and Health where he conducted dose reconstructions for epidemiologic studies of workers within the U.S. nuclear weapons complex, designed occupational studies to evaluate worker exposures from ionizing and nonionizing radiation, conducted numerous health hazard evaluations and served on the initial Anthrax Environmental Clearance Committee that set the clearance criteria to reoccupy the Hart Senate Office Building in 2002. He currently serves as a Health Physicist on the Environmental Protection Agency (EPA) Chemical, Biological, Radiological, and Nuclear Consequence Management Advisory Team to provide scientific and technical support within various levels of the government from local to international partners on several radiological issues including (1) emergency response, (2) risk assessment, (3) policy development, (3) decontamination technologies, and (4) environmental assessment and characterization. He is the Radiation Program Manager for the agency's airborne radiological detection capability known as the Airborne Spectral Photometric Environmental Collection Technology. He also is an Assistant Adjunct Professor at the University of Cincinnati Medical College, Department of Environmental Health. Dr. Cardarelli is a Captain in the U.S. Public Health Service (PHS) and served as the President of the Military Health Physics Section of the Health Physics Society. He served on the Food and Drug Administration's Technical Electronic Product Radiation Safety Standards Committee; NCRP Scientific Committees SC 2-1 (Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism) and NCRP SC 5-1 (Approach to Optimizing Decision Making for Late-Phase Recovery from Nuclear or Radiological Terrorism Incidents). He has received several PHS and non-PHS awards, most notably the EPA, PHS, and Federal Engineer-of-the-Year awards in 2006 and the John C. Villforth Leadership Award in 2009.

Michael A. Noska (*Consultant*) is the Senior Advisor for Health Physics, the Agency Radiation Safety Officer, and the Team Lead for Radiological Emergency Response at the U.S. Food and Drug Administration (FDA). He has been a health physicist with the U.S. Public Health Service (PHS) for 21 y and has had multiple assignments at the National Institutes of Health and the FDA with a focus on internal radiation dosimetry and radiological emergency preparedness and response. Prior to joining the PHS, Captain Noska worked as a research assistant in radiopharmaceutical laboratories at Harvard Medical School and Duke University Medical Center developing radiolabeled monoclonal antibodies for the treatment of cancer. He received his MS from the University of North Carolina School of Public Health as a Department of Energy Applied Health Physics Fellow. Captain Noska is the current Chair of the Federal Advisory Team for the Environment, Food and Health and a member of the Federal Radiological Preparedness Coordinating Committee. He is also the Past Chair of the Environmental Health Officer Professional Advisory Committee to the U.S.

Surgeon General and Past President of the Baltimore-Washington Chapter of the Health Physics Society. Captain Noska serves on several interagency committees and workgroups related to radiological emergency response. In 2011, he deployed to Japan as part of a team from the U.S. Department of Health and Human Services in support of the U.S. Ambassador following the Great Tohoku Earthquake and the nuclear crisis at the Fukushima Dai-ichi Nuclear Power Plant.

John A. MacKinney (*Consultant*) is the Director of Nuclear and Radiological Policy at the U.S. Department of Homeland Security (DHS). Mr. MacKinney has 24 y of experience in radiation science and risk, emergency protective action guides, technology and policy for long-term cleanup, research and development, nuclear weapons effects in urban areas, terrorism prevention, and science and policy to counter the nuclear terrorism threat. Mr. MacKinney advises and supports the Secretary of Homeland Security and the Assistant Secretary for Policy in all matters related to nuclear and radiological policy, especially terrorism prevention, response and recovery, and coordinates departmental and interagency policy development and programs to counter nuclear and radiological terrorism. Specific policy initiatives of Mr. MacKinney include requirements for response to a terrorist nuclear attack, long-term cleanup policy after acts of nuclear or radiological terrorism, counterterrorism response policy, and deterrence of weapons of mass destruction terrorism. In his Policy Director position, Mr. MacKinney represents DHS to the White House for all nuclear and radiological matters, coordinating policy development with the White House and other federal departments. He has served on a number of senior-level White House National Security Council (NSC), Homeland Security Council (HSC), and Office of Science and Technology Policy (OSTP) committees and working groups, including the HSC Scenarios Writing Group, the NSC/HSC Counterproliferation Technology Coordination Committee, the OSTP Radiological Dispersal Device (RDD) and Improvised Nuclear Device (IND) Subcommittee and Working Group, the OSTP Nuclear Defense Research and Development Subcommittee, all NSC Countering Nuclear Threats Policy Subcommittees, and special groups dedicated to the development of Presidential policy directives. Mr. MacKinney has served as an expert consultant to the World Bank on nuclear and radiological issues. He previously worked at the U.S. Environmental Protection Agency's Radiation Protection Division, and the National Homeland Security Research Center where he led a team of researchers investigating solutions for RDD and IND attack response and recovery. Mr. MacKinney holds a BS in Geology from Wheaton College (Wheaton, Illinois), an MS in Geophysics from the University of Wisconsin, and a MPH from the Johns Hopkins University, School of Public Health. He is certified in risk assessment and policy through the Risk Sciences and Public Policy Institute.

Steve Frey (*NCRP Staff Consultant*) is semi retired certified health physicist with over 20 y of experience in the profession, the last 17 y of which were in radiation safety program design and management. He began his venture into health physics by earning an MS in health sciences with a major in health physics at Purdue University in 1981. Dr. Frey's first professional assignments in health physics took place in the nuclear power industry. He served as a radioanalyst at Three Mile Island, which included computer modeling of reactor building source terms in support of the Unit 2 post accident recovery program, performing radioactive waste-stream characterizations, producing solutions for the computerizing radiological databases, and off-site emergency preparedness. His career eventually moved into administrative functions, including budgeting for and management of multi-million dollar program budgets. Dr. Frey served as the health and safety manager and radiation safety officer (RSO) at a radioactive waste volume-reduction facility, and then as the regulatory and safety director and RSO with two prominent manufacturers of radioactively-labeled compounds for biomedical research and radioimmunological assay kits. He last served full time in the profession at the Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory, where he was both the Radiological Control Manager and Head of the Operational Health Physics Department, and then later was the Assistant Director of the Environmental Safety and Health Division, Price Anderson Amendments Act Coordinator, and Integrated Safety Management System Coordinator. During his career, Dr. Frey successfully applied for and received eight radioactive material licenses (and assisted on two others), wrote the first successful Radiation Protection Program Implementation Plan at the SLAC National Accelerator Facility, and penned two successful Radiation Program Action Plans for the natural gas industry in Pennsylvania. He also served as a board director on the California Radioactive Materials Management Forum during its effort to help the Southwest Compact secure a low level radioactive material disposal site in the Mojave Desert Compact. Steve Frey currently serves several clients. Presently, he serves NCRP as the technical staff consultant for SC 5 1 (Decision Making for Late Phase Recovery from Nuclear or Radiological Incidents), and to other clients on a consulting basis as well.

The NCRP

The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection.
2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations.
3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection.
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units and measurements and with radiation protection.

The Council is the successor to the unincorporated association of scientists known as the National Committee on Radiation Protection and Measurements and was formed to carry on the work begun by the Committee in 1929.

The participants in the Council's work are the Council members and members of scientific and administrative committees. Council members are selected solely on the basis of their scientific expertise and serve as individuals, not as representatives of any particular organization. The scientific committees, composed of experts having detailed knowledge and competence in the particular area of the committee's interest, draft proposed recommendations. These are then submitted to the full membership of the Council for careful review and approval before being published.

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Fred A. Mettler, Jr. (2014) *On the Shoulders of Giants: Radiation Protection Over 50 Years*

John E. Till (2013) *When Does Risk Assessment Get Fuzzy?*

Antone L. Brooks (2012) *From the Field to the Laboratory and Back: The "What Ifs," "Wows," and "Who Cares" of Radiation Biology*

Eleanor A. Blakely (2011) *What Makes Particle Radiation so Effective?*

Charles E. Land (2010) *Radiation Protection and Public Policy in an Uncertain World*

John D. Boice, Jr. (2009) *Radiation Epidemiology: The Golden Age and Remaining Challenges*

Dade W. Moeller (2008) *Radiation Standards, Dose/Risk Assessments, Public Interactions, and Yucca Mountain: Thinking Outside the Box*

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Warren K. Sinclair (1993) *Science, Radiation Protection and the NCRP*
Edward W. Webster (1992) *Dose and Risk in Diagnostic Radiology: How Big? How Little?*
Victor P. Bond (1991) *When is a Dose Not a Dose?*
J. Newell Stannard (1990) *Radiation Protection and the Internal Emitter Saga*
Arthur C. Upton (1989) *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future*
Bo Lindell (1988) *How Safe is Safe Enough?*
Seymour Jablon (1987) *How to be Quantitative about Radiation Risk Estimates*
Herman P. Schwan (1986) *Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions*
John H. Harley (1985) *Truth (and Beauty) in Radiation Measurement*
Harald H. Rossi (1984) *Limitation and Assessment in Radiation Protection*
Merril Eisenbud (1983) *The Human Environment—Past, Present and Future*
Eugene L. Saenger (1982) *Ethics, Trade-Offs and Medical Radiation*
James F. Crow (1981) *How Well Can We Assess Genetic Risk? Not Very*
Harold O. Wyckoff (1980) *From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review*
Hymer L. Friedell (1979) *Radiation Protection—Concepts and Trade Offs*
Sir Edward Pochin (1978) *Why be Quantitative about Radiation Risk Estimates?*
Herbert M. Parker (1977) *The Squares of the Natural Numbers in Radiation Protection*

Currently, the following committees are actively engaged in formulating recommendations:

Program Area Committee 1: Basic Criteria, Epidemiology, Radiobiology, and Risk

- SC 1-20 Biological Effectiveness of Photons as a Function of Energy
- SC 1-21 Multiplatform National Approach for Providing Guidance on Integrating Basic Science and Epidemiological Studies on Low-Dose Radiation Biological and Health Effects
- SC 1-22 Radiation Protection for Astronauts in Short-Term Missions
- SC 1-23 Guidance on Radiation Dose Limits for the Lens of the Eye
- SC 1-24 Radiation Exposures in Space and the Potential for Central Nervous System Effects

Program Area Committee 2: Operational Radiation Safety

- SC 2-6 Radiation Safety Aspects of Nanotechnology
- SC 2-7 Radiation Safety of Sealed Radioactive Sources

Program Area Committee 3: Nuclear and Radiological Security and Safety

Program Area Committee 4: Radiation Protection in Medicine

SC 4-5 Radiation Protection in Dentistry Supplement: Cone Beam Computed Tomography, Digital Imaging and Handheld Dental Imaging
SC 4-6 Administrative Policies for Managing Substantial Dose Procedures and Tissue Reactions Associated with Fluoroscopically-Guided Interventions

Program Area Committee 5: Environmental Radiation and Radioactive Waste Issues

Program Area Committee 6: Radiation Measurements and Dosimetry

SC 6-8 Operation TOMODACHI Radiation Dose Assessment Peer Review
SC 6-9 U.S. Radiation Workers and Nuclear Weapons Test Participants Radiation Dose Assessment

Program Area Committee 7: Radiation Education, Risk Communication, Outreach, and Policy

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. Collaborating Organizations provide a means by which NCRP can gain input into its activities from a wider segment of society. At the same time, the relationships with the Collaborating Organizations facilitate wider dissemination of information about the Council's activities, interests and concerns. Collaborating Organizations have the opportunity to comment on draft reports (at the time that these are submitted to the members of the Council). This is intended to capitalize on the fact that Collaborating Organizations are in an excellent position to both contribute to the identification of what needs to be treated in NCRP reports and to identify problems that might result from proposed recommendations. The present Collaborating Organizations with which NCRP maintains liaison are as follows:

American Academy of Dermatology
American Academy of Environmental Engineers
American Academy of Health Physics
American Academy of Orthopaedic Surgeons
American Association of Physicists in Medicine
American Brachytherapy Society
American College of Cardiology
American College of Medical Physics
American College of Nuclear Physicians
American College of Occupational and Environmental Medicine
American College of Radiology
American Conference of Governmental Industrial Hygienists
American Dental Association

American Industrial Hygiene Association
American Institute of Ultrasound in Medicine
American Medical Association
American Nuclear Society
American Pharmaceutical Association
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society for Radiation Oncology
American Society of Emergency Radiology
American Society of Health-System Pharmacists
American Society of Nuclear Cardiology
American Society of Radiologic Technologists
American Thyroid Association
Association of Educators in Imaging and Radiological Sciences
Association of University Radiologists
Bioelectromagnetics Society
Campus Radiation Safety Officers
College of American Pathologists
Conference of Radiation Control Program Directors, Inc.
Council on Radionuclides and Radiopharmaceuticals
Defense Threat Reduction Agency
Electric Power Research Institute
Federal Aviation Administration
Federal Communications Commission
Federal Emergency Management Agency
Genetics Society of America
Health Physics Society
Institute of Electrical and Electronics Engineers, Inc.
Institute of Nuclear Power Operations
International Brotherhood of Electrical Workers
International Society of Exposure Science
National Aeronautics and Space Administration
National Association of Environmental Professionals
National Center for Environmental Health/Agency for Toxic Substances
National Electrical Manufacturers Association
National Institute for Occupational Safety and Health
National Institute of Standards and Technology
Nuclear Energy Institute
Office of Science and Technology Policy
Paper, Allied-Industrial, Chemical and Energy Workers International Union
Product Stewardship Institute
Radiation Research Society
Radiological Society of North America
Society for Cardiovascular Angiography and Interventions
Society for Pediatric Radiology
Society for Risk Analysis
Society of Cardiovascular Computed Tomography

Society of Chairmen of Academic Radiology Departments
Society of Interventional Radiology
Society of Nuclear Medicine and Molecular Imaging
Society of Radiologists in Ultrasound
Society of Skeletal Radiology
U.S. Air Force
U.S. Army
U.S. Coast Guard
U.S. Department of Energy
U.S. Department of Housing and Urban Development
U.S. Department of Labor
U.S. Department of Transportation
U.S. Environmental Protection Agency
U.S. Navy
U.S. Nuclear Regulatory Commission
U.S. Public Health Service
Utility Workers Union of America

NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of NCRP relates to the Special Liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the Special Liaison Program:

Australian Radiation Laboratory
Bundesamt fur Strahlenschutz (Germany)
Canadian Association of Medical Radiation Technologists
Canadian Nuclear Safety Commission
Central Laboratory for Radiological Protection (Poland)
China Institute for Radiation Protection
Commissariat a l'Energie Atomique (France)
Commonwealth Scientific Instrumentation Research Organization
  (Australia)
European Commission
Heads of the European Radiological Protection Competent Authorities
Health Council of the Netherlands
Health Protection Agency
International Commission on Non-Ionizing Radiation Protection
International Commission on Radiation Units and Measurements
International Commission on Radiological Protection
International Radiation Protection Association
Japanese Nuclear Safety Commission
Japan Radiation Council

Korea Institute of Nuclear Safety
Russian Scientific Commission on Radiation Protection
South African Forum for Radiation Protection
World Association of Nuclear Operators
World Health Organization, Radiation and Environmental Health

NCRP values highly the participation of these organizations in the Special Liaison Program.

The Council also benefits significantly from the relationships established pursuant to the Corporate Sponsor's Program. The program facilitates the interchange of information and ideas and corporate sponsors provide valuable fiscal support for the Council's program. This developing program currently includes the following Corporate Sponsors:

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The Council's activities have been made possible by the voluntary contribution of time and effort by its members and participants and the generous support of the following organizations:

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American College of Occupational and Environmental Medicine
American College of Radiology
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American Healthcare Radiology Administrators
American Industrial Hygiene Association
American Insurance Services Group
American Medical Association
American Nuclear Society
American Osteopathic College of Radiology
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
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American Society of Radiologic Technologists

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Canberra Industries, Inc.
Chem Nuclear Systems
Center for Devices and Radiological Health
Centers for Disease Control and Prevention
College of American Pathologists
Committee on Interagency Radiation Research and Policy Coordination
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Florida Institute of Phosphate Research
Florida Power Corporation
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Health Effects Research Foundation (Japan)
Health Physics Society
ICN Biomedicals, Inc.
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Motorola Foundation
National Aeronautics and Space Administration
National Association of Photographic Manufacturers
National Cancer Institute
National Electrical Manufacturers Association
National Institute of Standards and Technology
New York Power Authority
Nuclear Energy Institute
Philips Medical Systems
Picker International

Public Service Electric and Gas Company
Radiation Research Society
Radiological Society of North America
Richard Lounsbery Foundation
Sandia National Laboratory
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Society of Nuclear Medicine and Molecular Imaging
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Initial funds for publication of NCRP reports were provided by a grant from the James Picker Foundation.

NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities.

NCRP Publications

NCRP publications can be obtained online in both PDF and hardcopy formats at http://NCRPpublications.org. Professional societies can arrange for discounts for their members by contacting NCRP. Additional information on NCRP publications may be obtained from the NCRP website (http://NCRPonline.org) or by telephone (301-657-2652, ext. 25) and fax (301-907-8768). The mailing address is:

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Abstracts of NCRP reports published since 1980, abstracts of all NCRP commentaries, and the text of all NCRP statements are available at the NCRP website. Currently available publications are listed below.

NCRP Reports

No.	Title
8	*Control and Removal of Radioactive Contamination in Laboratories* (1951)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [includes Addendum 1 issued in August 1963]
25	*Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
36	*Radiation Protection in Veterinary Medicine* (1970)
37	*Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides* (1970)
38	*Protection Against Neutron Radiation* (1971)
40	*Protection Against Radiation from Brachytherapy Sources* (1972)
41	*Specification of Gamma-Ray Brachytherapy Sources* (1974)
42	*Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)
44	*Krypton-85 in the Atmosphere—Accumulation, Biological Significance, and Control Technology* (1975)
46	*Alpha-Emitting Particles in Lungs* (1975)
47	*Tritium Measurement Techniques* (1976)
49	*Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV* (1976)

50 *Environmental Radiation Measurements* (1976)
52 *Cesium-137 from the Environment to Man: Metabolism and Dose* (1977)
54 *Medical Radiation Exposure of Pregnant and Potentially Pregnant Women* (1977)
55 *Protection of the Thyroid Gland in the Event of Releases of Radioiodine* (1977)
57 *Instrumentation and Monitoring Methods for Radiation Protection* (1978)
58 *A Handbook of Radioactivity Measurements Procedures*, 2nd ed. (1985)
60 *Physical, Chemical, and Biological Properties of Radiocerium Relevant to Radiation Protection Guidelines* (1978)
61 *Radiation Safety Training Criteria for Industrial Radiography* (1978)
62 *Tritium in the Environment* (1979)
63 *Tritium and Other Radionuclide Labeled Organic Compounds Incorporated in Genetic Material* (1979)
64 *Influence of Dose and Its Distribution in Time on Dose-Response Relationships for Low-LET Radiations* (1980)
65 *Management of Persons Accidentally Contaminated with Radionuclides* (1980)
67 *Radiofrequency Electromagnetic Fields—Properties, Quantities and Units, Biophysical Interaction, and Measurements* (1981)
68 *Radiation Protection in Pediatric Radiology* (1981)
69 *Dosimetry of X-Ray and Gamma-Ray Beams for Radiation Therapy in the Energy Range 10 keV to 50 MeV* (1981)
70 *Nuclear Medicine—Factors Influencing the Choice and Use of Radionuclides in Diagnosis and Therapy* (1982)
72 *Radiation Protection and Measurement for Low-Voltage Neutron Generators* (1983)
73 *Protection in Nuclear Medicine and Ultrasound Diagnostic Procedures in Children* (1983)
74 *Biological Effects of Ultrasound: Mechanisms and Clinical Implications* (1983)
75 *Iodine-129: Evaluation of Releases from Nuclear Power Generation* (1983)
76 *Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment* (1984)
77 *Exposures from the Uranium Series with Emphasis on Radon and Its Daughters* (1984)
78 *Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States* (1984)
79 *Neutron Contamination from Medical Electron Accelerators* (1984)
80 *Induction of Thyroid Cancer by Ionizing Radiation* (1985)
81 *Carbon-14 in the Environment* (1985)
82 *SI Units in Radiation Protection and Measurements* (1985)
83 *The Experimental Basis for Absorbed-Dose Calculations in Medical Uses of Radionuclides* (1985)

84 *General Concepts for the Dosimetry of Internally Deposited Radionuclides* (1985)
86 *Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields* (1986)
87 *Use of Bioassay Procedures for Assessment of Internal Radionuclide Deposition* (1987)
88 *Radiation Alarms and Access Control Systems* (1986)
89 *Genetic Effects from Internally Deposited Radionuclides* (1987)
90 *Neptunium: Radiation Protection Guidelines* (1988)
92 *Public Radiation Exposure from Nuclear Power Generation in the United States* (1987)
93 *Ionizing Radiation Exposure of the Population of the United States* (1987)
94 *Exposure of the Population in the United States and Canada from Natural Background Radiation* (1987)
95 *Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources* (1987)
96 *Comparative Carcinogenicity of Ionizing Radiation and Chemicals* (1989)
97 *Measurement of Radon and Radon Daughters in Air* (1988)
99 *Quality Assurance for Diagnostic Imaging* (1988)
100 *Exposure of the U.S. Population from Diagnostic Medical Radiation* (1989)
101 *Exposure of the U.S. Population from Occupational Radiation* (1989)
102 *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use)* (1989)
103 *Control of Radon in Houses* (1989)
104 *The Relative Biological Effectiveness of Radiations of Different Quality* (1990)
105 *Radiation Protection for Medical and Allied Health Personnel* (1989)
106 *Limit for Exposure to "Hot Particles" on the Skin* (1989)
107 *Implementation of the Principle of As Low As Reasonably Achievable (ALARA) for Medical and Dental Personnel* (1990)
108 *Conceptual Basis for Calculations of Absorbed-Dose Distributions* (1991)
109 *Effects of Ionizing Radiation on Aquatic Organisms* (1991)
110 *Some Aspects of Strontium Radiobiology* (1991)
111 *Developing Radiation Emergency Plans for Academic, Medical or Industrial Facilities* (1991)
112 *Calibration of Survey Instruments Used in Radiation Protection for the Assessment of Ionizing Radiation Fields and Radioactive Surface Contamination* (1991)
113 *Exposure Criteria for Medical Diagnostic Ultrasound: I. Criteria Based on Thermal Mechanisms* (1992)
114 *Maintaining Radiation Protection Records* (1992)
115 *Risk Estimates for Radiation Protection* (1993)
116 *Limitation of Exposure to Ionizing Radiation* (1993)
117 *Research Needs for Radiation Protection* (1993)
118 *Radiation Protection in the Mineral Extraction Industry* (1993)

119 *A Practical Guide to the Determination of Human Exposure to Radiofrequency Fields* (1993)
120 *Dose Control at Nuclear Power Plants* (1994)
121 *Principles and Application of Collective Dose in Radiation Protection* (1995)
122 *Use of Personal Monitors to Estimate Effective Dose Equivalent and Effective Dose to Workers for External Exposure to Low-LET Radiation* (1995)
123 *Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground* (1996)
124 *Sources and Magnitude of Occupational and Public Exposures from Nuclear Medicine Procedures* (1996)
125 *Deposition, Retention and Dosimetry of Inhaled Radioactive Substances* (1997)
126 *Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection* (1997)
127 *Operational Radiation Safety Program* (1998)
128 *Radionuclide Exposure of the Embryo/Fetus* (1998)
129 *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies* (1999)
130 *Biological Effects and Exposure Limits for "Hot Particles"* (1999)
131 *Scientific Basis for Evaluating the Risks to Populations from Space Applications of Plutonium* (2001)
132 *Radiation Protection Guidance for Activities in Low-Earth Orbit* (2000)
133 *Radiation Protection for Procedures Performed Outside the Radiology Department* (2000)
134 *Operational Radiation Safety Training* (2000)
135 *Liver Cancer Risk from Internally-Deposited Radionuclides* (2001)
136 *Evaluation of the Linear-Nonthreshold Dose-Response Model for Ionizing Radiation* (2001)
137 *Fluence-Based and Microdosimetric Event-Based Methods for Radiation Protection in Space* (2001)
138 *Management of Terrorist Events Involving Radioactive Material* (2001)
139 *Risk-Based Classification of Radioactive and Hazardous Chemical Wastes* (2002)
140 *Exposure Criteria for Medical Diagnostic Ultrasound: II. Criteria Based on all Known Mechanisms* (2002)
141 *Managing Potentially Radioactive Scrap Metal* (2002)
142 *Operational Radiation Safety Program for Astronauts in Low-Earth Orbit: A Basic Framework* (2002)
143 *Management Techniques for Laboratories and Other Small Institutional Generators to Minimize Off-Site Disposal of Low-Level Radioactive Waste* (2003)
144 *Radiation Protection for Particle Accelerator Facilities* (2003)
145 *Radiation Protection in Dentistry* (2003)
146 *Approaches to Risk Management in Remediation of Radioactively Contaminated Sites* (2004)
147 *Structural Shielding Design for Medical X-Ray Imaging Facilities* (2004)

148 *Radiation Protection in Veterinary Medicine* (2004)
149 *A Guide to Mammography and Other Breast Imaging Procedures* (2004)
150 *Extrapolation of Radiation-Induced Cancer Risks from Nonhuman Experimental Systems to Humans* (2005)
151 *Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities* (2005)
152 *Performance Assessment of Near-Surface Facilities for Disposal of Low-Level Radioactive Waste* (2005)
153 *Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit* (2006)
154 *Cesium-137 in the Environment: Radioecology and Approaches to Assessment and Management* (2006)
155 *Management of Radionuclide Therapy Patients* (2006)
156 *Development of a Biokinetic Model for Radionuclide-Contaminated Wounds and Procedures for Their Assessment, Dosimetry and Treatment* (2006)
157 *Radiation Protection in Educational Institutions* (2007)
158 *Uncertainties in the Measurement and Dosimetry of External Radiation* (2007)
159 *Risk to the Thyroid from Ionizing Radiation* (2008)
160 *Ionizing Radiation Exposure of the Population of the United States* (2009)
161 *Management of Persons Contaminated with Radionuclides* (2008)
162 *Self Assessment of Radiation-Safety Programs* (2009)
163 *Radiation Dose Reconstruction: Principles and Practices* (2009)
164 *Uncertainties in Internal Radiation Dose Assessment* (2009)
165 *Responding to a Radiological or Nuclear Terrorism Incident: A Guide for Decision Makers* (2010)
167 *Potential Impact of Individual Genetic Susceptibility and Previous Radiation Exposure on Radiation Risk for Astronauts* (2010)
168 *Radiation Dose Management for Fluoroscopically-Guided Interventional Medical Procedures* (2010)
169 *Design of Effective Radiological Effluent Monitoring and Environmental Surveillance Programs* (2010)
170 *Second Primary Cancers and Cardiovascular Disease After Radiation Therapy* (2011)
171 *Uncertainties in the Estimation of Radiation Risks and Probability of Disease Causation* (2012)
172 *Reference Levels and Achievable Doses in Medical and Dental Imaging: Recommendations for the United States* (2012)
173 *Investigation of Radiological Incidents* (2012)
174 *Preconception and Prenatal Radiation Exposure: Health Effects and Protective Guidance* (2013)
175 *Decision Making for Late-Phase Recovery from Major Nuclear or Radiological Incidents* (2014)

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Volume XLIV. NCRP Reports Nos. 170, 171
Volume XLV. NCRP Reports Nos. 172, 173

(Titles of the individual reports contained in each volume are given previously.)

NCRP Commentaries

No.	Title
1	*Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
4	*Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5	*Review of the Publication, Living Without Landfills* (1989)
6	*Radon Exposure of the U.S. Population—Status of the Problem (1991)*
7	*Misadministration of Radioactive Material in Medicine—Scientific Background* (1991)
8	*Uncertainty in NCRP Screening Models Relating to Atmospheric Transport, Deposition and Uptake by Humans* (1993)
9	*Considerations Regarding the Unintended Radiation Exposure of the Embryo, Fetus or Nursing Child* (1994)
10	*Advising the Public about Radiation Emergencies: A Document for Public Comment* (1994)
11	*Dose Limits for Individuals Who Receive Exposure from Radionuclide Therapy Patients* (1995)
12	*Radiation Exposure and High-Altitude Flight* (1995)
13	*An Introduction to Efficacy in Diagnostic Radiology and Nuclear Medicine (Justification of Medical Radiation Exposure)* (1995)
14	*A Guide for Uncertainty Analysis in Dose and Risk Assessments Related to Environmental Contamination* (1996)
15	*Evaluating the Reliability of Biokinetic and Dosimetric Models and Parameters Used to Assess Individual Doses for Risk Assessment Purposes* (1998)
16	*Screening of Humans for Security Purposes Using Ionizing Radiation Scanning Systems* (2003)
17	*Pulsed Fast Neutron Analysis System Used in Security Surveillance* (2003)
18	*Biological Effects of Modulated Radiofrequency Fields* (2003)
19	*Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism* (2005)
20	*Radiation Protection and Measurement Issues Related to Cargo Scanning with Accelerator-Produced High-Energy X Rays* (2007)
21	*Radiation Protection in the Application of Active Detection Technologies* (2011)
22	*Radiological Health Protection Issues Associated With Use of Active Detection Technology Systems for Detection of Radioactive Threat Materials* (2011)
23	*Radiation Protection for Space Activities: Supplement to Previous Recommendations* (2014)

Proceedings of the Annual Meeting

No.	Title
1	*Perceptions of Risk,* Proceedings of the Fifteenth Annual Meeting held on March 14-15, 1979 (including Taylor Lecture No. 3) (1980)
3	*Critical Issues in Setting Radiation Dose Limits*, Proceedings of the Seventeenth Annual Meeting held on April 8-9, 1981 (including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Approaches,* Proceedings of the Eighteenth Annual Meeting held on April 6-7, 1982 (including Taylor Lecture No. 6) (1983)
5	*Environmental Radioactivity,* Proceedings of the Nineteenth Annual Meeting held on April 6-7, 1983 (including Taylor Lecture No. 7) (1983)
6	*Some Issues Important in Developing Basic Radiation Protection Recommendations*, Proceedings of the Twentieth Annual Meeting held on April 4-5, 1984 (including Taylor Lecture No. 8) (1985)
7	*Radioactive Waste*, Proceedings of the Twenty-First Annual Meeting held on April 3-4, 1985 (including Taylor Lecture No. 9)(1986)
8	*Nonionizing Electromagnetic Radiations and Ultrasound,* Proceedings of the Twenty-Second Annual Meeting held on April 2-3, 1986 (including Taylor Lecture No. 10) (1988)
9	*New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates*, Proceedings of the Twenty-Third Annual Meeting held on April 8-9, 1987 (including Taylor Lecture No. 11) (1988)
10	*Radon*, Proceedings of the Twenty-Fourth Annual Meeting held on March 30-31, 1988 (including Taylor Lecture No. 12) (1989)
11	*Radiation Protection Today—The NCRP at Sixty Years*, Proceedings of the Twenty-Fifth Annual Meeting held on April 5-6, 1989 (including Taylor Lecture No. 13) (1990)
12	*Health and Ecological Implications of Radioactively Contaminated Environments*, Proceedings of the Twenty-Sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991)
13	*Genes, Cancer and Radiation Protection,* Proceedings of the Twenty-Seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992)
14	*Radiation Protection in Medicine,* Proceedings of the Twenty-Eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No. 16) (1993)
15	*Radiation Science and Societal Decision Making,* Proceedings of the Twenty-Ninth Annual Meeting held on April 7-8, 1993 (including Taylor Lecture No. 17) (1994)
16	*Extremely-Low-Frequency Electromagnetic Fields: Issues in Biological Effects and Public Health*, Proceedings of the Thirtieth Annual Meeting held on April 6-7, 1994 (not published).
17	*Environmental Dose Reconstruction and Risk Implications,* Proceedings of the Thirty-First Annual Meeting held on April 12-13, 1995 (including Taylor Lecture No. 19) (1996)

18 *Implications of New Data on Radiation Cancer Risk*, Proceedings of the Thirty-Second Annual Meeting held on April 3-4, 1996 (including Taylor Lecture No. 20) (1997)

19 *The Effects of Pre- and Postconception Exposure to Radiation*, Proceedings of the Thirty-Third Annual Meeting held on April 2-3, 1997, Teratology **59**, 181–317 (1999)

20 *Cosmic Radiation Exposure of Airline Crews, Passengers and Astronauts*, Proceedings of the Thirty-Fourth Annual Meeting held on April 1-2, 1998, Health Phys. **79**, 466–613 (2000)

21 *Radiation Protection in Medicine: Contemporary Issues*, Proceedings of the Thirty-Fifth Annual Meeting held on April 7-8, 1999 (including Taylor Lecture No. 23) (1999)

22 *Ionizing Radiation Science and Protection in the 21st Century*, Proceedings of the Thirty-Sixth Annual Meeting held on April 5-6, 2000, Health Phys. **80**, 317–402 (2001)

23 *Fallout from Atmospheric Nuclear Tests—Impact on Science and Society*, Proceedings of the Thirty-Seventh Annual Meeting held on April 4-5, 2001, Health Phys. **82**, 573–748 (2002)

24 *Where the New Biology Meets Epidemiology: Impact on Radiation Risk Estimates*, Proceedings of the Thirty-Eighth Annual Meeting held on April 10-11, 2002, Health Phys. **85**, 1–108 (2003)

25 *Radiation Protection at the Beginning of the 21st Century–A Look Forward*, Proceedings of the Thirty-Ninth Annual Meeting held on April 9–10, 2003, Health Phys. **87**, 237–319 (2004)

26 *Advances in Consequence Management for Radiological Terrorism Events*, Proceedings of the Fortieth Annual Meeting held on April 14–15, 2004, Health Phys. **89**, 415–588 (2005)

27 *Managing the Disposition of Low-Activity Radioactive Materials*, Proceedings of the Forty-First Annual Meeting held on March 30–31, 2005, Health Phys. **91**, 413–536 (2006)

28 *Chernobyl at Twenty*, Proceedings of the Forty-Second Annual Meeting held on April 3–4, 2006, Health Phys. **93**, 345–595 (2007)

29 *Advances in Radiation Protection in Medicine*, Proceedings of the Forty-Third Annual Meeting held on April 16-17, 2007, Health Phys. **95**, 461–686 (2008)

30 *Low Dose and Low Dose-Rate Radiation Effects and Models*, Proceedings of the Forty-Fourth Annual Meeting held on April 14–15, 2008, Health Phys. **97**, 373–541 (2009)

31 *Future of Nuclear Power Worldwide – Health, Safety, and Environment*, Proceedings of the Forty-Fifth Annual Meeting held on March 2–3, 2009, Health Phys. **100**(1), 2–112 (2011)

32 *Communication of Radiation Benefits and Risks in Decision Making*, Proceedings of the Forty-Sixth Annual Meeting held March 8–9, 2010, Health Phys. **101**(5), 497–629 (2011)

33 *Scientific and Policy Challenges of Particle Radiations in Medical Therapy and Space Missions*, Proceedings of the Forty-Seventh Annual Meeting held on March 7–8, 2011, Health Phys. **103**(5), 529–684 (2012)

34 *Emerging Issues in Radiation Protection in Medicine, Emergency Response, and the Nuclear Fuel Cycle*, Proceedings of the

Forty-Eighth Annual Meeting held March 12–13, 2012, Health Phys. **105**(5), 401–468 (2013)

35 *Radiation Dose the Impacts on Exposed Populations*, Proceedings of the Forty-Ninth Annual Meeting held March 11–12, 2013, Health Phys. **106**(2), 145–339 (2014)

Lauriston S. Taylor Lectures

No.	Title
1	*The Squares of the Natural Numbers in Radiation Protection by* Herbert M. Parker (1977)
2	*Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [available also in *Perceptions of Risk*, see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980)
5	*How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [available also in *Critical Issues in Setting Radiation Dose Limits*, see above]
6	*Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [available also in *Radiation Protection and New Medical Diagnostic Approaches*, see above]
7	*The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [available also in *Environmental Radioactivity*, see above]
8	*Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]
9	*Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [available also in *Radioactive Waste*, see above]
10	*Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions* by Herman P. Schwan (1987) [available also in *Nonionizing Electromagnetic Radiations and Ultrasound*, see above]
11	*How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above]
12	*How Safe is Safe Enough?* by Bo Lindell (1988) [available also in *Radon*, see above]
13	*Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [available also in *Radiation Protection Today*, see above]
14	*Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [available also in *Health and Ecological Implications of Radioactively Contaminated Environments*, see above]
15	*When is a Dose Not a Dose?* by Victor P. Bond (1992) [available also in *Genes, Cancer and Radiation Protection*, see above]
16	*Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992) [available also in *Radiation Protection in Medicine*, see above]

17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993) [available also in *Radiation Science and Societal Decision Making,* see above]

18 *Mice, Myths and Men* by R.J. Michael Fry (1995)

19 *Certainty and Uncertainty in Radiation Research* by Albrecht M. Kellerer. Health Phys. **69**, 446–453 (1995)

20 *70 Years of Radiation Genetics: Fruit Flies, Mice and Humans* by Seymour Abrahamson. Health Phys. **71**, 624–633 (1996)

21 *Radionuclides in the Body: Meeting the Challenge* by William J. Bair. Health Phys. **73**, 423–432 (1997)

22 *From Chimney Sweeps to Astronauts: Cancer Risks in the Work Place* by Eric J. Hall. Health Phys. **75**, 357–366 (1998)

23 *Back to Background: Natural Radiation and Radioactivity Exposed* by Naomi H. Harley. Health Phys. **79**, 121–128 (2000)

24 *Administered Radioactivity: Unde Venimus Quoque Imus* by S. James Adelstein. Health Phys. **80**, 317–324 (2001)

25 *Assuring the Safety of Medical Diagnostic Ultrasound* by Wesley L. Nyborg. Health Phys. **82**, 578–587 (2002)

26 *Developing Mechanistic Data for Incorporation into Cancer and Genetic Risk Assessments: Old Problems and New Approaches* by R. Julian Preston. Health Phys. **85**, 4–12 (2003)

27 *The Evolution of Radiation Protection–From Erythema to Genetic Risks to Risks of Cancer to ?* by Charles B. Meinhold, Health Phys. **87**, 240–248 (2004)

28 *Radiation Protection in the Aftermath of a Terrorist Attack Involving Exposure to Ionizing Radiation* by Abel J. Gonzalez, Health Phys. **89**, 418–446 (2005)

29 *Nontargeted Effects of Radiation: Implications for Low Dose Exposures* by John B. Little, Health Phys. **91**, 416–426 (2006)

30 *Fifty Years of Scientific Research: The Importance of Scholarship and the Influence of Politics and Controversy* by Robert L. Brent, Health Phys. **93**, 348–379 (2007)

31 *The Quest for Therapeutic Actinide Chelators* by Patricia W. Durbin, Health Phys. **95**, 465–492 (2008)

32 *Yucca Mountain Radiation Standards, Dose/Risk Assessments, Thinking Outside the Box, Evaluations, and Recommendations* by Dade W. Moeller, Health Phys. **97**, 376–391 (2009)

33 *Radiation Epidemiology-the Golden Age and Future Challenges* by John D. Boice, Jr., Health Phys. **100**(1), 59–76 (2011)

34 *Radiation Protection and Public Policy in an Uncertain World* by Charles E. Land, Health Phys. **101**(5), 499–508 (2011)

35 *What Makes Particle Radiation so Effective?* by Eleanor A. Blakely, Health Phys. **103**(5), 508–528 (2012)

36 *From the Field to the Laboratory and Back: The What Ifs, Wows, and Who Cares of Radiation Biology*, by Antone L. Brooks, Health Phys. **105**(5), 407–421 (2013)

37 *When Does Risk Assessment Get Fuzzy?*, by John E. Till, Health Phys. **106**(2), 148-161 (2014)

38 *On the Shoulders of Giants: Radiation Protection Over 50 Years*, by Fred A. Mettler, Jr.

Symposium Proceedings

No.	Title
1	*The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack*, Proceedings of a Symposium held April 27-29, 1981 (1982)
2	*Radioactive and Mixed Waste—Risk as a Basis for Waste Classification,* Proceedings of a Symposium held November 9, 1994 (1995)
3	*Acceptability of Risk from Radiation—Application to Human Space Flight,* Proceedings of a Symposium held May 29, 1996 (1997)
4	*21st Century Biodosimetry: Quantifying the Past and Predicting the Future*, Proceedings of a Symposium held February 22, 2001, Radiat. Prot. Dosim. **97**(1), (2001)
5	*National Conference on Dose Reduction in CT, with an Emphasis on Pediatric Patients*, Summary of a Symposium held November 6-7, 2002, Am. J. Roentgenol. **181**(2), 321–339 (2003)

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No.	Title
1	"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63**, 428 (1954)
2	"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. **84**, 152 (1960) and Radiology **75**, 122 (1960)
3	*X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968)
4	*Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements* (1973)
5	*NCRP Statement on Dose Limit for Neutrons* (1980)
6	*Control of Air Emissions of Radionuclides* (1984)
7	*The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992)
8	*The Application of ALARA for Occupational Exposures* (1999)
9	*Extension of the Skin Dose Limit for Hot Particles to Other External Sources of Skin Irradiation* (2001)
10	*Recent Applications of the NCRP Public Dose Limit Recommendation for Ionizing Radiation* (2004)

Other Documents

The following documents were published outside of the NCRP report, commentary and statement series:

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Dose Effect Modifying Factors in Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service, Springfield, Virginia)

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