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Edited by Michele Laraia

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Michele Laraia

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To my wife Giovanna and my children, Silvia and Luca:
thanks for being there for me before, during, and
after the development of this book.

Contents

List of contributors

C.A. Negin CANegin&Associates, Washington Grove, MD, United States

P.M. Booth Hylton Environmental, Cheshire, United Kingdom

F. Borrman iUS Institut für Umwelttechnologien und Strahlenschutz GmbH (Institute for Environmental Technology and Radiation Protection), Aschaffenburg, Germany

M. Božik Nuclear and Decommissioning Company, plc., Bratislava, Slovakia

H. Farr Radiation Safety and Control Services, Stratham, NH, United States

M. Hornacek Slovak University of Technology in Bratislava, Bratislava, Slovakia

T. Hrncir Slovak University of Technology in Bratislava, Bratislava; DECOM, Trnava, Slovakia

J. Kaulard Private Consultant, Aachen, Germany

T.S. LaGuardia LaGuardia & Associates, LLC, Sanibel, FL, United States

M. Laraia Independent consultant, Rome, Italy

K. Lauridsen Consultant, Roskilde, Denmark

M. Listjak Slovak University of Technology in Bratislava, Bratislava; VUJE, Trnava, Slovakia

A.F. McWhirter New Build Nuclear Consulting Ltd., West Kilbride, United Kingdom

H. Rindo Institute of Applied Energy (IAE), Tokyo, Japan

D. Stelmakh Chornobyl NPP, Slavutich, Ukraine

M. Zachar Slovak University of Technology in Bratislava, Bratislava; DECOM, Trnava, Slovakia

Editor biography

Michele Laraia, a chemical engineer by background, obtained his first degree at the University of Rome. In 1975 he began to work at Italy's Regulatory Body, and since 1982 he held the role of licensing manager of decommissioning projects. Starting in Jul. 1991, Michele worked at the International Atomic Energy Agency, Waste Technology Section, as Unit Leader responsible for decontamination and decommissioning of nuclear installations and environmental remediation. The objectives of the work were to provide guidance to Member States on the planning and implementation of nuclear decommissioning and site remediation, to disseminate information on good practices, and to provide direct assistance to Member States in the implementation of their programs. Following his retirement in Nov. 2011, Michele offers consultant services in the abovementioned areas.

Preface

M. Laraia
Independent consultant, Rome, Italy

Nuclear decommissioning has been a mature industry (and a mature science) for at least 10–15 years. The cessation of major R&D programs (national, e.g., under the aegis of the US Department of Energy, and international, e.g., by the European Commission) around the year 2000 ideally signaled a general understanding that the basic decommissioning technology was available worldwide. Since then, technological efforts have aimed at optimizing methods and techniques, but no major breakthroughs have emerged. As of today, it is commonly accepted that the industry can effectively deal with almost all cases of nuclear decommissioning, with exceptions remaining for large facilities that had been affected by severe accidents resulting in exceedingly high contamination and irradiation levels. Other difficult-to-decommission facilities include those that were built at the beginning of the nuclear era, when design and operation criteria were much less stringent than they are today. And yet, the experience being gained from the decommissioning of Fukushima, especially from the wide use of robots and other remotely operated technology, can influence the decommissioning strategies more than currently appears to do: it is not unthinkable that in the not-too-far future a fleet of robots will do a high portion of decommissioning work instead of humans. But for this to happen (a real breakthrough, indeed!), robotics costs should become more affordable and robots should become more versatile. A full chapter has been given in this book to explain the decommissioning process after a severe accident.

As mentioned above, to do justice to technological progress, decommissioning is a mature industry. Therefore a few years ago I was tasked with editing of Laraia [1], which was a consolidated summary of all decommissioning aspects that prevailed at that time. Decommissioning is multifaceted (or multidisciplinary): Laraia [1] dealt with such aspects as assessment of decommissioning strategies, safety and radiation protection, decontamination and dismantling, waste management, planning, redevelopment of decommissioned sites, and international experiences. Laraia [1] was intended for those embarking in nuclear decommissioning as newcomers or upgrading their skills to a new field. It provided comprehensive knowledge of decommissioning as standalone science. To this end, the book maintains its usefulness to date.

Six years have not passed in vain. It was already evident in 2011—when the book was completed—that decommissioning should have not been examined only from the angle of technology. For example, there were chapters in Laraia [1] about stakeholder involvement and the organization and management of decommissioning projects. The "soft side" of decommissioning had already come to light; but, as that book provided a summary of the basic knowledge of the time, it gave more emphasis to the consolidated aspects of decommissioning and less emphasis to the emerging aspects.

It is assumed that the large pool of decommissioning experts at work today, including a network of companies and independent consultants specializing in decommissioning as a whole and in specific aspects of it—vendors, suppliers, and all those who make decommissioning an international “market”—need to familiarize themselves with aspects that were not deemed essential in 2012. Laraia [1] maintains its role of providing background information and guidance and should be usefully read or consulted as a precursor to this book.

Therefore the chapters that follow, while being a follow-up to Laraia [1] as far as general progress is concerned, and more and more experience and feedback is being gained, cast light also on new areas.

In regard to advances, this book expands on emerging technologies. As said above, while no major technological breakthroughs are expected in the near future, a continual flow of advances contributes to making decommissioning a safer and more cost-effective technology. If one refers to the automobile industry, it can be stated that car manufacturing has been a mature industry for at least 50 years, yet more recent advances like the anti-lock braking system have significantly improved the safety of driving. Likewise the growing use of lasers as cutting or decontamination tools has greatly added to the accuracy and efficiency of decommissioning.

Another chapter deals with new international recommendations in safety and radiation protection and their application to decommissioning. In this regard the key milestone can be attributed to the 2014 publication of the new edition of the Basic Safety Standards (BSS), sponsored by the IAEA and a number of other international organizations. In the field of decommissioning, it is expected that the BSS will contribute to achieve harmonization of national approaches to decommissioning, especially as far as clearance criteria are concerned.

To provide examples of growing experience, this book addresses the post-2012 decommissioning of nuclear power plants worldwide, and a chapter that did not exist in Laraia [1] discusses the decommissioning of research reactors. The sheer number of research reactors that have reached the end of their service lives and are planning for and implementing decommissioning worldwide (at least 100 reactors), and the diversity and uniqueness of research reactor features make them an ideal target for a dedicated chapter.

Experience has shown that decommissioning (i.e., dismantling) and environmental remediation projects on the same site are both aimed at reducing hazards and/or achieving a common end state for the facility and its site. Therefore, decommissioning and remediation should be ideally viewed in conjunction since they require the integration and optimization of infrastructure (i.e., human, scientific, and financial resources). The integrated management of decommissioning and remediation is expected to more consistently achieve the site end objectives and require less post-decommissioning remediation work and more manageable institutional control. A dedicated chapter of this book provides some examples and scenarios in which decommissioning and remediation projects developed in an integrated fashion should produce successful outcomes.

As said initially in this preface, the period that elapsed since the publication of Laraia [1] has seen the appearance of new lines of thought, as well as innovations. In other words, there are aspects of decommissioning that were not given adequate attention in the past and these are more important now because other more traditional issues have been solved.

To begin with, the cultural changes taking place in an organization transitioning from operations to decommissioning require attention. The cultural issues of a decommissioning project (e.g., workers' backgrounds, sense of ownership, or team spirit), though contributing to a considerable portion of all decommissioning-related incidents and near-misses, have yet to be thoroughly reviewed, and it time that this experience is discussed; therefore, a chapter is devoted to this in this book.

Culture includes people and human factors. The goal of the chapter on decommissioning culture is to provide information regarding cultural issues, their impacts on activities, and anticipated challenges due to culture.

Given the long timescales of decommissioning projects (100 years or more, especially if early and detailed planning is included), the preservation of well-understood information and its transfer to subsequent generations and responsible organizations are vital elements of the decommissioning industry. Future players will need to know enough about contaminated facilities and sites so that they are aware of the remaining hazards and make risk-informed decisions concerning the safety, security, and ultimate redevelopment of the site. The information must be preserved in a form that can be retrieved, understood, and usable over a long period of time.

A dedicated chapter stresses the fact that the planning and implementation of decommissioning generates a considerable amount of information, which can be incorporated in records, and in the tacit knowledge accumulated by those directly involved in these activities. So far the decommissioning community has instead focused on the technological aspects of record preservation (e.g., longevity). While these studies remain important, there have been only a few examples where the conceptual issues of an integrated and comprehensive (i.e., open to all stakeholders) knowledge management system have been addressed.

Another chapter of this book is given to the financial aspects of decommissioning. On one hand, there are projects where the very fact that several players are ready to bid for a contract implies that there must be a "real cost" of decommissioning; on the other hand, diverging, escalating costs of decommissioning projects are often quoted as evidence of the uncertainties still looming on this topic. Decommissioning cost estimations can vary considerably both within and across countries, even for similar facilities. These differences may have good technical reasons but make the process of reviewing estimates difficult and the estimates themselves vulnerable to criticism. Therefore, the recent publication of the International Structure for Decommissioning Costing (ISDC) of Nuclear Installations by the OECD Nuclear Energy Agency (NEA), the International Atomic Energy Agency (IAEA), and the European Commission (EC) intended to propose an internationally-accepted, standard structure of decommissioning cost items either directly for the production of cost estimates or for purposes of comparison. This and other innovations in the financial field of decommissioning are discussed in the pages that follow.

Another chapter deals with unexpected events and findings during the decommissioning of nuclear facilities, and the lessons learned from those events. They have often been referred to as "unknowns"; however, many of the problems encountered during decommissioning were well known, but they simply were not given enough attention. In some other cases, the problem may not have been ever encountered by the decommissioning team, prompting the sudden development of new tools and procedures with inevitable delays and extra costs. In this chapter, examples of actions, decisions, or omissions are given and some analysis has been performed to identify the underlying causes that may lead to unexpected difficulties during decommissioning. The chapter evaluates the need for, and implications of, using lessons learned to prepare for possible occurrences; it also discusses how to mitigate the impacts of any such occurrences.

In a dedicated chapter of Laraia [1] the term "stakeholders" had been used mostly to designate the local communities. This is not the case for a "follow-up" chapter in this book, where non-local categories of the populace and various public interests are also addressed. Stakeholders addressed in this book are not just those living in the vicinity of the nuclear installation under decommissioning. In fact, impacts from a large project can be felt in distant countries (e.g., in financial terms or in image). It is therefore essential for those responsible for a decommissioning project to identify all possible stakeholders at the onset of a project and to start a dialogue with no unnecessary delay.

Finally, a new trend has emerged in recent years. Previously it was de facto assumed that the (radiological) end state of a decommissioned site should be unrestricted release (greenfield). Likewise, it was assumed that materials resulting from decommissioning should be either released as nonradioactive for unrestricted release or disposed of as radioactive waste. Experience has shown that less expensive, intermediate options are possible; the site itself could be subject to restricted release (brownfield) or the materials and waste arising from decommissioning could be released in a predetermined condition or for predefined uses. Another chapter of this book deals with these innovations.

The target groups of this book are decision-makers, plant operators, contractors, waste managers, and regulators involved in planning, management, authorization, and execution of decommissioning activities. The report is particularly relevant for those responsible for nuclear facilities approaching the end of their foreseen lifetime. The report should also be of interest for the designers and builders of new nuclear installations: to date it is a general requirement that the design and construction of nuclear installations should include full consideration of eventual decommissioning. It is assumed that the readers will have basic knowledge of such disciplines as nuclear physics, radiation protection, and waste management.

This book is based on presenting, discussing, and exchanging information on international experience, lessons learned (not leaving out mishaps and near-misses), issues, and challenges in planning for and implementing the decommissioning of nuclear installations. Special focus is given to international (especially IAEA's) positions, recommendations, and guidelines inherent to all aspects of decommissioning. As a practical means to ensuring success, the book is imbued with a sense of realism. To this end, wide use is made of case studies, facts-of-life and anecdotal evidence. As decommissioning is a multidisciplinary process, an integrated approach is pursued and single aspects are considered from multiple angles.

In summary, the objective of the book (especially when read in conjunction with its predecessor) [1] is to produce competent, professional planners and project managers able to prepare decommissioning plans, to identify all factors and constraints relevant to the decision-making, and to specify the resource requirements for their particular situations. Therefore the book aims at assisting the readers to become “smart buyers” of the necessary specialty services required.

Finally, it should be recognized that part of the information and guidance imparted by this book may also be relevant to entire national programs (not necessarily nuclear ones) and their decision-makers: for example, aspects such as the sharing of technologies (e.g., the know-how) and transfer of knowledge (e.g., training and lessons learned) between projects may be readily extended to all installations nationwide or internationally. And people who are not directly responsible for decommissioning but have interests in it and concerns about it (the stakeholders) should also read the book.

Reference

[1] M. Laraia (Ed.), Nuclear Decommissioning: Planning, Execution and International Experience, Woodhead, Cambridge, ISBN: 978-0-85709-115-4, 2012.

Introduction

1

M. Laraia
Independent consultant, Rome, Italy

1.1 Introduction

If one looks at the shutdown rate of nuclear facilities (especially reactors) and decommissioning strategies country by country, many novelties have emerged since 2011, when the publishing process of Ref. [1] was almost complete.

Due to time constraints the impacts of the Fukushima accident (Mar. 2011) were scarcely taken into account in the drafting of Ref. [1]. Full consideration to decommissioning a reactor after a severe accident is given in this book (Chapter 9). The immediate impact of the Fukushima accident has been the premature shutdown of a number of power reactors in Japan (which was to be expected) and in Germany (more surprisingly). Apart from these two countries, the other nuclear countries chose not to shut down their generating reactors on account of the Fukushima accident (but some countries chose to slow down or temporarily cancel the construction of new units).

As highlighted below, the circumstances in the United Kingdom and the United States deserve special considerations in that they exemplify typical factors and trends in reactor shutdown and decommissioning strategies worldwide.

In the United States, the early retirements of six nuclear reactors over the last few years have been a major blow to the nuclear industry. Two purely economic retirements (Kewaunee and Fort Calhoun, both single-reactor sites), one due to tax and local opposition (Vermont Yankee, one reactor), and three based on unbearable costs of repairs (Crystal River, one reactor, and San Onofre, two reactors) indicate that there is a variety of operational and economic problems. The reactors that were shut down were not competitive because the United States has the technical ability and plentiful, diverse resources to meet the need for electricity with less expensive and less risky options [2].

Other nuclear utilities made it known that several more reactors may close down within the next couple of years and reach the decommissioning phase. Some of these have had their operating licenses extended an additional 20 years, but this factor has not been enough to reverse the trend towards early retirement.

As of late, the US Energy Information Administration (EIA) noted that in the current market, if old reactors need significant repair, it may not be worthwhile to do so and extend operation. The EIA stated “Lower Power Prices and Higher Repair Costs Drive Nuclear Retirements” [3]. But the situation is more complicated than that; it is not only reactors in bad condition that are at near risk of shutdown. As old reactors become more costly to manage, they may become uneconomic to stay in operation. Actually, the first reactor that retired in 2013 (Kewaunee) was in good operating condition and had just had its license extended for 20 years, but its owners concluded it

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could not compete and would soon start producing losses in the electricity market, so the decision was made to decommission it.

First, in most parts of the United States, the electricity price is set by natural gas. In those areas where the wholesale price of electricity is set by the market, prices have been decreasing considerably. In parallel, the demand for electricity has been decreasing due to growing efficiency of electricity-consuming equipment. While nuclear fuel costs are currently low, nuclear power plant (NPP) operation and maintenance costs and ongoing capital costs are high. As reactors age, these costs rise. If a reactor is inefficient (i.e., high operating costs), needs major repairs, or safety retrofits are in order, it can be easily pushed beyond the point of nonprofitability.

The second factor is reliability. In the years 2011 and 2012 there were frequent and prolonged outages. Most outages were due to large reactors with operational problems (among those being Crystal River, San Onofre). The reactors with the longest outages, and related high repair costs, Crystal River and San Onofre, have permanently been shut down. It should also be noted that older reactors have shorter refueling cycles, 18 months, than newer reactors, which have 24 months. Therefore, over time older reactors are inevitably doomed to lower load factors.

Third, small units that stand alone—geographically or organizationally—will typically have higher costs and are more prone to premature shutdowns (e.g., Fort Calhoun). These factors generally reflect economies of scale because large, multiunit sites integrated into corporate fleets of reactors can share operational costs.

Fourth, the Fukushima effect poses more serious challenges as older reactors tend to become more distant from the state-of-the-art appreciation of safety. Responding to growing safety concerns may become too costly for existing reactors, because modernization of older plants is made difficult by their designs.

The foregoing overview clearly shows that the rate of decommissioning projects in the US and elsewhere is going to rise over the next 2 or 3 decades. This trend is not due to the gradual expiration of service lives (as it was believed only some years ago) but to political and economic factors. Along with these developments and taking account of the high costs, the industry will have to constantly upgrade and optimize resources to achieve smooth and cost-effective completion of decommissioning projects. The following sections of the Introduction highlight new challenges that are coming to the attention of planners and implementers. These challenges were hardly addressed by Ref. [1] and it is felt that they need proper coverage in this book.

There are a few clear lessons from US decommissioning projects that are underway. First, the project tends to take longer and be more expensive than planned. Second, the long-term storage of spent nuclear fuel on-site considerably impacts the local communities, which was not anticipated at the onset of the nuclear project and will not be offset by social benefits. This damage is significant because it tends to cause a tension between the utility, the regulators, and local stakeholders. And experience has shown that in order to be successful, decommissioning should be based on sound working relationships between all stakeholders.

Experiences in the United States highlight another trend, namely the transfer of decommissioning responsibility (and licenses) from the former operating organization to one devoted only to decommissioning. In Spain, the transfer of decommissioning responsibility to the state-owned company ENRESA has been legally enforced for many years, but this has remained an almost unique national approach until now. The new US trend was already anticipated in Ref. [1, Chapter 2] for the Zion NPP case.

The recent Lacrosse NPP case in the United States confirms the trend [4]. The US Nuclear Regulatory Commission approved the Lacrosse license transfer from the Dairyland Power Cooperative to LaCrosse Solutions LLC, a subsidiary of radioactive waste disposal and decommissioning company Energy Solutions LLC (currently responsible for Zion decommissioning). The move was intended to speed up decommissioning of the long-shutdown small boiling water reactor (BWR). In contractual terms, Dairyland will remain the owner of the La Crosse site and will be in charge of the spent fuel storage (possibly extending long after completion of the reactor decommissioning). LaCrosse Solutions will be the decommissioning licensee.

It has been recently learned that this form of ownership transfer may regard other shutdown reactors, e.g., Vermont Yankee.

The traditional decommissioning strategy for the United Kingdom's Magnox reactors has been for many years a long-term safe enclosure (called "care and maintenance" in the United Kingdom). Following reactor defueling and preparatory activities for safe enclosure, final dismantling is deferred up to 100 years. But recently the Nuclear Decommissioning Authority (NDA) stated it was time to question this long-held assumption:

> *Whilst we will celebrate as the first few sites are made safe and secure for a long period of quiescence, it is hard to ignore the question of what comes next. Increasingly we find ourselves questioning whether the baseline strategy is appropriate as a blanket strategy for all reactors in the Magnox fleet.*
>
> *Ref. [5].*

Ongoing research has identified two major issues with a long-term safe enclosure. First, it had originally been estimated that radioactive decay over many decades would allow activated waste to decategorize to low-level waste (LLW)—less expensive and less hazardous to manage and dispose of. However, more recently it has been demonstrated that even after the long safe enclosure phase a major portion of the Magnox decommissioning waste will still not be eligible for LLW management.

Secondly, an updated cost model seems to infer the reduction in decommissioning costs over long periods of safe enclosure—for example, resulting from eased accessibility—is mostly offset by the significant costs of preparing for and managing the safe enclosure.

Thirdly, NDA-driven research proved that even after many decades of safe enclosure remote techniques would still be required for Magnox dismantling to minimize industrial risks and occupational exposures, which further reduces cost benefits. The increasing deterioration of structures, systems, and components over the long periods of safe enclosure could increase dismantling costs even more.

NDA highlighted more risks associated with long-term safe enclosure, such as loss of skills, records and plant knowledge, managing assets (e.g., land) that could be profitably diverted to other uses, uncertainty over changing regulations, and occasional events such as the collapse of financial markets.

At present there is another factor that seems to push utilities in many countries toward accelerated dismantling. In the past, many utilities deferred decommissioning to accrue real (i.e., above inflation) interests to decommissioning funds. Over the past few years, as the global economy worsened and central banks decreased interest rates, utilities have been unable to rely on high returns on investments.

Therefore, deferred decommissioning has become less profitable. Reportedly, many decommissioning funds declined in performance. In parallel, decommissioning costs seem to continue to rise.

As a result of these developments in some countries, utilities are more likely to move to total, immediate decommissioning before the financial balance worsens.

A different trend has emerged elsewhere over the last few years. The management of the decommissioning of a number of multiunit sites within a national program may be inadequate or inappropriate if based on approaches and strategies developed for single-unit sites (see Chapter 12 for more detail). The varied nature of activities undertaken, their interfaces, and their interdependencies are likely to affect the management of decommissioning. These issues can be more acute where some facilities are entering the decommissioning phase while others are still operational or even new facilities are being built. Therefore, greater attention is now being paid to optimizing the decommissioning of facilities and sites within the overall decommissioning program in a country; one example follows.

The Chooz A reactor, which shut down in 1991, is the first pressurized-water reactor (PWR) dismantling project in France. Feedback from the Chooz project will be used to optimize the forthcoming decommissioning of the entire fleet of French PWRs, incorporate synergies, and ultimately reduce decommissioning schedules and costs. For example, the French nuclear operator (EDF) assumes significant savings from the standardization of equipment across its fleet-wide program (e.g., cutting tools for reactor vessel internals, first tested at Chooz). EDF can benefit from being engineer-architect for all its NPPs, allowing it to gather firsthand expertise from all the lifecycle phases, from design to decommissioning [6].

In fact, the nationwide approach to decommissioning in France has a strategic outcome, quite opposite to the trend of immediate dismantling that is prevailing in other countries. EDF has recently revised and considerably slowed down the decommissioning strategy for the long-shutdown gas-cooled reactors (GCRs), focusing first on the full decommissioning of one such reactor to gain experience for the others. As a consequence the dismantling of a whole GCR fleet may be delayed for decades [7,8].

In summary, it appears that the traditional debate between immediate vs. deferred dismantling is still far from a conclusion on the global scale: each country will pursue an independent policy based on national circumstances and priorities.

1.2 Planning

The primary responsibility for planning and implementing a decommissioning project stays with the operating organization (the licensee). However, there are certain high-level responsibilities about national infrastructure, industrial priorities, education, etc., that belong to the government. A fundamental International Atomic Energy Agency (IAEA) reference [9] reads,

> *The government shall establish and maintain a governmental, legal and regulatory framework within which all aspects of decommissioning, including management of the resulting radioactive waste, can be planned and carried out safely. This framework shall include a clear allocation of responsibilities, provision of independent regulatory functions and requirements in respect of financial assurance for decommissioning.*

Governmental responsibilities are often described in terms of policy and strategy. Chapter 2 expands on the decisive role that safety and radiation protection requirements exert on the trends of the decommissioning industry.

It appears that the old IAEA estimate of the size of world's decommissioning market until 2050 [10] still holds—disregarding inflation, currency exchange variations, etc. because fluctuations of these parameters are included within the order of magnitude. In 2004 the IAEA estimated that the overall decommissioning budget would be around *One Trillion Dollars*. Military installations would be responsible for half of that figure. Recent estimates confirm certain components of this old assumption. For example Reuters [11] reports that the International Energy Agency (IEA) stated that almost 200 of the 434 reactors in operation would be permanently shut down by 2040, and it estimated the cost of decommissioning them to be more than $100 billion (later on the IEA pointed out that $100 billion was just a tentative estimate, and the real cost could be as much as twice as high). In fact many experts feel that 500 million dollars per reactor (the basis of IEA estimate) is too low a figure. Moreover these figures do not include the cost of spent fuel storage and waste disposal.

Although the decommissioning technology might become less expensive (but so far there are no signs that the scale factor and the maturity of the industry are pushing costs down), the cost of spent fuel repositories is largely unknown.

The US Nuclear Regulatory Commission estimates that the cost of decommissioning in the United States—with some 100 reactors—ranges from $300 million to $400 million per reactor, but experience has shown that some reactors might cost much more. French authorities estimate the country's decommissioning bill to be between 28 billion and 32 billion euros ($30–$32 billion). German utilities have set aside 36 billion euros, which they claim is adequate—regardless of opposing views. In Japan the cost of decommissioning the country's 48 reactors is estimated at around $30 billion.

The United Kingdom's bill for decommissioning and waste disposal is now estimated at 117 billion pounds ($154 billion) [7,8], more than double the estimate made 10 years ago.

In addition to reactors, nuclear fuel cycle facilities (front- and back-end) are going to be decommissioned. There are hundreds of these facilities, and the cost of their decommissioning is unlikely to be less than that of the reactors. All in all, the global impressive figure of *One Trillion Dollars* quoted by IAEA [10] as an order of magnitude is still valid.

The reader should note that the overall costs of decommissioning quoted above do not take into account *when* individual facilities will be shut down within the next 30–40 years. The cost figures refer to the whole pool of nuclear facilities in operation or already shut down.

Cost estimates for the decommissioning of nuclear facilities vary significantly from country to country, even for similar facilities. These variations may have often sound, technical reasons but render the review and comparison of cost estimates difficult and vulnerable. Therefore, the cooperation between the OECD Nuclear Energy Agency (NEA), the IAEA, and the European Commission (EC) that resulted in the publication of Ref. [12] was intended to produce a standard structure of decommissioning cost items either for cost estimation or to allow a meaningful comparison of costs ("apples to apples, oranges to oranges"). International Structure for Decommissioning Costing (ISDC) [12] updates an earlier cost structure dating back to 1999. The revised structure has aimed to include all foreseeable costs within any given decommissioning project [12] and other advances in cost estimates are addressed in Chapter 5.

A national policy should typically include the following elements: defined safety and security objectives, allocation of national responsibilities and resources for decommissioning arrangements, identification of the main approaches for decommissioning, provisions for managing the radioactive waste generated, and provisions for public information and participation. The IAEA has published a report on policy and strategy of decommissioning [13]. The foregoing can be promptly read in knowledge management (KM) terms because KM is indeed an intrinsic part of decommissioning. IAEA [9] states the following: "Ensuring that the necessary scientific and technical expertise is available both for the licensee and for the support of regulatory review and other independent national review functions" has clear KM implications. Indeed KM is one of the new paradigms of the decommissioning, as will be highlighted in Chapter 4.

An integrated approach to KM is essential. The traditional treating of KM in isolation as a distinct activity is unlikely to bring any advantages.

Documented information, in the form of records, is critical to knowledge generation and maintenance. It is here that the integration begins. Any information package is always connected to other entities. These entities could be, for example, other sources of information, the originator of the information, or a description of the methodology used to create the information and data. Therefore the three aspects—people, documents and tools—should be viewed in conjunction. Another aspect is essential: the generation and the preservation of knowledge are the two sides of the same coin, because one cannot exist without the other.

The decommissioning strategy reflects and elaborates on the objectives and requirements established by in the national policy [13]. The strategy should take into account the specific conditions of the country in question in regard to decommissioning. This is especially pertinent to nations with limited resources and little or no experience in decommissioning. Relevant factors include, but are not be limited to, the following:

- Availability of scientific, technical, and financial resources
- Organizational structures of the responsible organization and regulatory body and their interactions
- Governmental direction and support, if any

- Potential impact of decommissioning on the local economy and on the local communities, and other stakeholders
- The cultural side: job market, leadership, team spirit, motivations, cross-cultural interactions, etc.

The last bullet of the above list calls for some elaboration. It is clear that the cultural aspects of decommissioning are heavily reflected in organization and management of decommissioning. For example, a dedicated effort is necessary in decommissioning to draft new work procedures, a tough task for those who may not have the full understanding of working in a hostile, partly unknown environment. A related aspect is that dismantling procedures can hardly be the same across the wide range of a facility’s conditions. Basically each room and each component may call for a distinct dismantling procedure. Another cultural issue is linked to external consultants or specialists recruited for limited periods of time for training purposes or for solving specific issues. The transfer of knowledge from external experts to the standing decommissioning organization (generally based on former operations staff) should ideally be accurate and comprehensive enough to allow the decommissioning organization to “digest” and use that knowledge in future instances. The problem can be exacerbated by the short duration of the expert assistance, which, due to contractual factors, is often restricted to problem-solving and does not extend to an effective, comprehensive knowledge transfer. Moreover, the external advisors will typically hold a different background from the decommissioning staff and may even speak a foreign language or jargon. The “soft issues” of decommissioning, especially its cultural side, are the new frontiers of this discipline: in this book, they are presented in Chapter 3.

The KM strategy must support and meet the expectations of all people concerned (the stakeholders); otherwise it has limited purpose. What are their needs? When do they need to know? In what form do they want to receive the knowledge?

There are many stakeholders with diverse interests in a decommissioning project. Their interests will range from the full extent of technological and managerial aspects to key indicators of progress and impacts: financial institutions will be interested in how efficiently the money is being spent, while the environmentalist will be concerned about radioactive effluents or the reduction of site contamination.

It can be useful to refer to the network of stakeholders. Each of them has individual interests and worries, but they will share information and interact with each other. The notion of network can be extended to the different “packets” of knowledge about the overall decommissioning package. One stakeholder may be content to know the general package features, but who should another stakeholder address to be informed about specific “packets” of the whole package? For example, who has the knowledge for advising on the transport of certain substances? This is not obvious a priori. Therefore stakeholders are involved in a two-way process: they need to get knowledge, while somebody responsible for the decommissioning project must deliver that knowledge. Therefore, communications with new stakeholders (e.g., the concerned man-on-the-street) will require technically competent staff who can additionally speak an understandable language. The emerging roles of decommissioning stakeholders are described in more detail in Chapter 6.

1.3 Execution

Chapter 7 shares important lessons learned from in-field experience, which are expected to facilitate decommissioning of nuclear sites. Stakeholders such as nuclear operators, regulators, government officials, and others are expected to benefit from brief summaries of the lessons, advantages, and drawbacks of decommissioning methods and tools, as well as links to any records containing more details. Generally, lessons learned is knowledge that could be of interest and orientation to the stakeholders. Lessons learned include positive or negative impacts. For example, lessons learned include significant and continual regulatory comments on submitted documents, post-incident inspections, issues that have come to the operators' attention and/or have been reviewed by the regulators, case studies delivering site-specific examples or good practices, or failures that should not repeated.

Sometimes the policy and strategy inherent to a national decommissioning program stem from nonnuclear, independently established policy and strategy of the government. One such example is taken from Dolphin [14]. The United Kingdom's Government Construction Strategy was published by the Cabinet Office on May 31, 2011. The report announced the government's intention to require collaborative 3D building information modeling (BIM) (with all project and asset information, documentation, and data being electronic) on its projects by 2016. Basically BIM is a process for sharing information throughout the entire lifecycle of an asset, from concept to demolition. A BIM model is a 3D model consisting of a variety of information-rich objects that, once combined, create an integrated representation of an entire asset.

Nuclear decommissioning can involve the construction of new facilities (e.g., waste stores, retrieval systems); the modification of existing structures (e.g., the deplanting of buildings, replacement of old equipment); and the demolition and removal of structures, systems, and components. In the strategy planned for the Magnox power stations in the United Kingdom the sites enter a safe enclosure period where the remaining assets must be properly maintained and inspected for almost one hundred years until they are finally removed. During safe enclosure and final dismantling health and safety information should remain at hand to future users in a way that it does not rely uniquely on individual skills. Dolphin [14] provides many examples of BIM applications to decommissioning.

One example of robotic development is given in the following, arbitrarily chosen among many prompted by the Fukushima 2011 accident in support of plant recovery and decommissioning [15]. Robots are frequently used in the nuclear industry to reach almost inaccessible or highly contaminated areas. At Fukushima, robots have been extensively used to survey the damage and more are being developed to undertake more complex tasks. To this end, versatility is vital. To name one application, Hitachi has supplied the remotely-controlled ASTACO-SoRa heavy-duty robot, which has been used for debris removal. Other robots have been launched by Mitsubishi, Toshiba, and Honda. Remotely controlled activities and robots are addressed in Chapter 9 of this book.

A submersible robot has been designed and manufactured by Hitachi to locate and assess leakage in buildings where radioactive water has accumulated during and after the accident. This robot (weight: 32 kg; height: 33 cm; length: 60 cm; width: 45 cm) is capable of traveling horizontally underwater or along the bottom of a pool, as well as vertically, for example, up a wall by suction. Being small, the robot can enter narrow spaces. The robot is operated via cable.

A shape-changing robot has been developed to inspect impervious parts of the plant. It consists of three segments: the main body and two crawlers. The robot can take a straight shape for passing through narrow spaces, such as 10-cm pipes. In another configuration, it can rotate its crawlers 90 degrees in respect to its main body to take a U-shape, with the crawlers ensuring stability when traveling over flat areas. See Ref. [16, Annex I-2] for more detail.

It has been known for years that laser cutting is a promising technique in decommissioning. However, safety, deployment, and reliability concerns have so far prevented this technology from becoming of commercial use. Recent developments are described in Ref. [17], which might finally trigger the emergence of laser cutting as a mature technology. TWI Ltd. is working with the United Kingdom's NDA and various site license companies in the country to develop laser cutting technologies for dismantling and size reduction. One of the technologies TWI has developed is a hand-held laser for cutting such metallic structures as piping, tanks, and supports in low-radiation areas. TWI has also manufactured lasers for remote in situ dismantling using a “snake-arm” robotic manipulator. It has also cooperated with Sellafield on lasers that can be used for cutting up dismissed fuel skips to achieve optimal filling of waste containers. Emerging technologies in nuclear decommissioning are described in Chapter 8.

Finally, Chapter 10 deals with the option (and opportunity) of releasing materials, buildings, and entire sites under restricted conditions or with a predefined fate. While the traditional end state of a decommissioning project (“greenfield”) is typically close to pristine (i.e., background) levels, experience suggests that in most cases where complete decommissioning has been achieved (delicensing of the site), completion of the works has been associated with prompt reuse of the site or buildings even when some minor contamination was still present (“brownfield”). Because of the value of the assets released by decommissioning, termination of one activity from the decommissioned site will lead to its reuse in a new activity. While eventually any decommissioned site will be reused to new purposes, the essential factor is time (and money): reuse should be integrated with decommissioning, even at the cost of some contamination remaining (provided that safety is ensured at all times). It is likely that the trend towards Brownfields and immediate site reuse will grow in the future due to economic factors, especially the practical impossibility or the excess costs to reach unrestricted release at heavily contaminated sites (e.g., large, old reactors or nuclear fuel cycle centers). Reuse/redevelopment of industrial sites is a field where much should be learned from the nonnuclear sector (Fig. 1.1).

1.4 International experience

The following describes the advances of some decommissioning projects since the early 2000s, with a focus on activities taking place after Ref. [1] was drafted. The projects described below are representative of various types of nuclear facilities. More

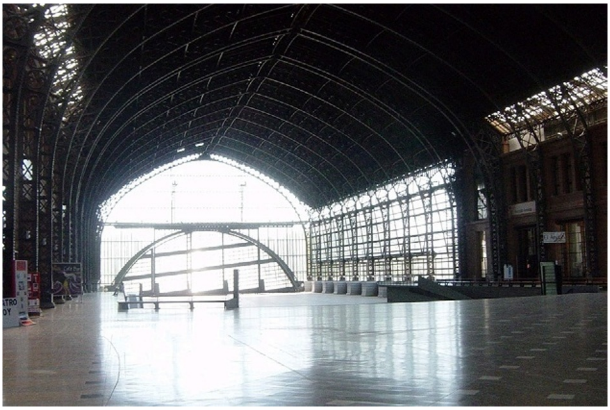

Fig. 1.1 Mapocho railway station converted to multicultural center, Santiago, Chile. Photo by M. Laraia, 2010.

information is given in dedicated chapters ([Chapter 11][Chapter 13]), for research reactors, and environmental remediation projects.

1.4.1 Garigliano NPP, Italy

In Italy, Trino, Latina, and Caorso NPPs were all shut down in 1986–87 following a national referendum. Garigliano NPP had already been shut down in 1982. The initial decommissioning strategy for Italian NPPs was "protective storage." But immediate dismantling was chosen by the government in 1999 for all Italian NPPs as a national strategy (the nuclear operator is a state-owned organization). Until recently practically no dismantling had started in radiologically controlled areas. In fact the following list shows that active dismantling started much later, subject to the promulgation of the official decommissioning (dismantling) license:

- Latina, in Dec. 2014
- Trino, in Aug. 2012
- Garigliano, in Sep. 2012
- Caorso, in Feb. 2014.

Fuel from Latina, Garigliano, and Caorso NPPs has been already shipped to France and the United Kingdom for reprocessing. Some fuel elements still remain in the Avogadro pool at Saluggia pending transfer abroad. High-level waste ("glass canisters") from fuel reprocessing will be returned from France and the United Kingdom to Italy to be temporarily stored into the future national repository (location is still to be determined).

Some activities aimed at "passive protection" had already begun following plant shutdowns and have continued since. Other activities started when the plants received a dismantling license.

Activities preparatory to nuclear decommissioning had been implemented soon after final shutdown in the 1980s and progressed continually until now. Predecommissioning activities (under and following the initial "protective storage" license) and radiological decommissioning activities (since the date of the new decommissioning license) are described for Garigliano NPP, as an example, in the following.

Garigliano NPP, a small BWR of General Electric conception, was in operation until 1978, when it was shut down for maintenance; it never restarted. In 1982 the plant was permanently shut down. In 1985 the plant obtained a license aimed at "protective storage" (safe enclosure, the national strategy in force at that time). The Garigliano plant was close to reaching "protective storage" when the change of strategy occurred in 1999. By then the reactor had already been defueled (1985–87) and no fuel remained on-site. The radiological characterization had been completed and safe enclosure of the reactor building and turbine building were achieved. All operational wastes have been processed; redundant waste tanks had been demolished and modifications of the systems for decommissioning purposes were in progress. The reactor circuits were drained, and, following defueling, the spent fuel pool was emptied and decontaminated from 1991 to 1993. This activity is described in Ref. [16, Annex I-2].

A waste treatment campaign addressed resins, sludge, and evaporator concentrates ($280\,m^3$) located in underground tanks. The campaign used a mobile cementation system and was carried out from 1997 to 1998. Some 1500 400-l drums were produced (either shielded or unshielded) [18].

In 1999, SOGIN (the state-owned national operator for decommissioning and waste management, which inherited the nuclear legacy from the former electric utility ENEL) took ownership of the plant with the aim of carrying out full site cleanup. In 2007, activities were completed for the removal of asbestos from the turbine building. In 2008, the electrical, ventilation, drainage, and liquid radiological monitoring systems for asbestos removal were restored. In 2009, "hot" and "cold" chemical laboratories were installed. In 2010 decontamination of the reactor building was completed, including removal of asbestos insulation.

The decree of environmental compatibility stated that the decommissioning activities will not affect the reactor and turbine buildings, designed by the famous architect Riccardo Morandi, which were declared part of Italy's architectural heritage as established by the Ministry of Heritage and Culture.

In Sep. 2012 a license was obtained for the dismantling of the power plant and the remediation of the site; it was issued by the Ministry of Economic Development, on the advice of the regulatory body (ISPRA) and other competent institutions. This license allowed dismantling of the nuclear "island" to begin.

The construction of the new radioactive liquid effluent treatment system began in 2014. The remediation of trenches (formerly used for on-site burial of radioactive waste) is underway. Buildings and ancillary facilities (ventilation, electrical systems) to be used for the remediation of the trenches have been either completed or are under construction [19]. This is one example of environmental remediation in the context of a decommissioning project, as further explained in Chapter 13 of this book.

Following completion of the turbine building deplanting (started in 2014) the building will be converted to temporarily store the Garigliano decommissioning waste, pending waste transfer to the (future) national repository.

In Mar. 2014 the process for demolishing the stack, which is 95-m tall, began: four operational phases are planned. In phase 1, a 12-m stack mockup was constructed to test the methods and tools that will be used in the actual dismantling of the stack. Then the stack structure was reinforced. The third phase included the top-down decontamination (scarification) of the stack's internal surfaces. The scarification was carried out by a robot of Italian design, which was remotely operated (completed in Jul. 2016). The fourth phase is the stack demolition. In the end a new smaller stack will be constructed [19]. One should note that the initial dismantling strategy for the stack was by explosives. The revised strategy takes into account the presence of adjacent nuclear buildings (Fig. 1.2).

The Garigliano decommissioning activities are planned to end in 2024 (or at the latest, taking contingencies into account, in 2028). By then the radioactive waste containers stored on-site will be ready for transfer to the National Repository, allowing for the reuse of the site without radiological restrictions.

It should be noted that the Italian decommissioning strategy of immediate dismantling, while in line with IAEA recommendations, can turn out to be somewhat overambitious in timing, especially in regard to reaching the greenfield status. This condition depends on the availability of a centralized national waste storage/disposal facility. The dismantling and the waste treatment activities can be fully implemented, but without a national repository, the conditioned waste has to be kept on-site in an interim store, impeding full release of the site and producing additional running costs. Therefore, the national strategy promulgated in 1999 called for the siting of the repository by 2005 and for its operation by 2009. Unfortunately both these targets have failed. In 1999 the availability of a national waste repository was considered a prerequisite for dismantling: in fact, international experience (e.g., the Greifswald NPP in Germany) has subsequently shown that interim on-site storage of waste is an acceptable option

Fig. 1.2 Garigliano NPP: the spherical reactor building with the stack in the background. Photo by M. Laraia, 1980s.

allowing prompt dismantling to proceed. Actually the four Italian NPPs are currently being dismantled without a national repository and the decommissioning wastes are being stored on-site.

It took many years (until 2012 and beyond) for nuclear dismantling to begin at the four Italian sites. There are many reasons for the delay. Local communities were against the on-site storage of decommissioning waste, as they feared that supposedly temporary stores will become permanent due to strong political hindrances to the siting of a centralized national storage/disposal facility. Trying to overcome local opposition, law No. 27/2012 on economic development was promulgated: through its Art. 24 it establishes new procedures to reduce the timing of the licensing phases for decommissioning activities with a strong involvement of local administrations. Another complicating factor could be that the main law regulating nuclear activities (DPR 230/1995) involves a number of state bodies (each with veto power) in the licensing of decommissioning activities. The siting of the national waste repository is still undecided. At the time of writing, the incumbent government has reiterated action to finalize the siting process soon.

1.4.2 Barsebäck NPP, Sweden

At Barsebäck NPP, the dismantling process began about 2 years after the plant was shut down. With a decommissioning period of about 5 years, a site can be expected to be released for other use about 7 years after shutdown. The regulators are concerned that a longer timetable will mean there will not be enough competent staff left to deal with the dismantling.

But decommissioning waste from Barsebäck cannot be disposed of until the disposal facility (SFR) has been extended and relicensed for short-lived, low- and intermediate-level decommissioning waste, which is expected to happen in 2023. Finally, perhaps taking care of regulatory inclinations, it appears that some dismantling is starting before 2023 (see the last part of the Section 1.4.2). It is estimated that the dismantling work will take some 5–7 years. Site release for unrestricted use is foreseen around 2029.

The two BWR units in Barsebäck were permanently shut down 1999 and 2005, respectively. Barsebäck 1 and 2 are two adjacent installations structurally linked via electrical buildings, control rooms, and personnel buildings. A number of process systems are also integrated between the units.

The facilities were prepared for a period of care and maintenance pending dismantling (offsite shipment of fuel, downsizing of organization, adjustment of supervision and maintenance, energy saving measures, etc.). A summary of the main activities to date include the following. See Refs. [20,21] and other references indicated below:

- Transport of spent fuel elements completed (Dec. 2006). Fuel was transferred to the interim storage facility (CLAB, Oskarshamn).
- Decontamination of the primary system (Dec. 2007–Jan. 2008) [22].
- Current activities in “service operation” (the Swedish term for “care and maintenance”) since Dec. 1, 2006. This means placing the plant in the lowest energy mode, reducing the

need for monitoring, minimizing residual safety risk, and optimizing the costs. Service operation will end in 2021 (subject to the status of the SFR extension works) when preparation for final dismantling starts and a new organizational structure is established.

- Characterization of materials and site (2009–2012) [23].
- Planning of decommissioning (taking into account Sweden‘s decommissioning approach—“rip & ship”).
- Stakeholder management/communication [21] (Fig. 1.3).
- The Barsebäck owner (BKAB) has built networks and competence by being a member of national and international committees (SKB, IAEA, OECD/NEA, WNA, WANO, EPRI, etc.).
- Rebuilding of the electricity systems and operation systems. The goal was to adjust the electrical systems for the actual demands and requirements for the service operation, to create a site easier to survey, and to reduce costs for operation and maintenance.
- The central control room has been unattended since Dec. 17, 2007 and the supervision of service operation is handled by a system of VDI (duty engineers) and LOP (alarm operators). VDI is on duty during 24 h per day. Guard personnel (BC) serve as LOP and make contact with VDI when an alarm activates. VDI is responsible for making decisions and taking steps should the need occur. BC is manned around-the-clock.
- Hazardous material such us turbine oil and chemicals has been removed from the site.
- Some preventive maintenance has been switched over to corrective maintenance.
- Inventory of existing documents is in progress.
- An overall decommissioning plan has been presented and accepted by the owner and the regulators Swedish Radiation Safety Authority (SSM).
- A new management system, a new safety analysis report and a new safety technical regulation for service operation has been created and approved by SSM.
- Operational waste is stored on-site. Core grids from the operational period are stored on-site in pools waiting for an approved transportation cask and will be sent to interim storage. Ion exchange masses from the operational period are stored in tanks. New equipment has been installed at Barsebäck to solidify these masses in concrete.

Fig. 1.3 Demonstration against the closure of Barsebäck NPP.
Credit: IAEA, 2009. An Overview of Stakeholder Involvement in Decommissioning Nuclear Energy Series No. NW-T-2.5.

The following describes in detail the most recent activities at Barsebäck. Segmentation of reactor internals is one of the most time consuming tasks within a nuclear decommissioning project. Barsebäck has established a project that includes segmentation and packaging of internal parts of the reactor tanks. The storage will be in a local newly built facility (Project HINT).

Project HINT includes four subprojects (plus regulatory approval):

1. Building of an interim storage facility for the reactor internals on-site, pending the availability of the final repository (SFR). The basic design has already been used in Forsmark NPP in Sweden. On Jul. 1, 2016, BKAB inaugurated the interim storage.
2. The segmentation work of the reactor internals started in late 2016 and will be finished in 2019. The internals will be segmented underwater in the reactor hall (RH) pools. They will then be put in steel tanks (unconditioned) and will be transported to the interim storage.
3. Modernization of RH overhead cranes due to new regulatory requirements.
4. Transportation and logistics from RH to interim storage (handling equipment).

On Nov. 2, 2015, it was disclosed that Westinghouse had been awarded a contract to dismantle the reactor pressure vessel internals [24]. Under the contract signed with plant operator BKAB, Westinghouse is to dismantle, segment, and package the reactor pressure vessel internals for final disposal. In order the carry out this work, Westinghouse will implement its proven, remotely controlled underwater mechanical cutting techniques and employ specifically designed equipment it will fabricate and test at its facilities in Västerås, Sweden. The project is expected to take about 4 years to complete.

1.4.3 The Georgia Tech Building, United States

Georgia Institute of Technology's Neely Research Center was a structure that at one time was connected to the school's 5-MW, heavy-water-cooled research reactor.

Originally in operation for more than 30 years, the building and the reactor were used frequently by the school's nuclear engineering students until the reactor was shut down in the late 1980s. The Georgia Tech (GT) Research Reactor was decommissioned in 1999–2001. The reactor vessel, concrete bioshield, and lead tank were removed.

However, the reactor's companion facility, where source encapsulation and other broad-scope research activities were conducted, still remained intact.

In 2012—after 12 years—the building that housed the reactor (called Neely Building) was characterized, internally decontaminated, and finally demolished to make way for the Marcus Nanotechnology Research Center [25].

The main decommissioning contractor was Ameriphysics, with Oak Ridge Associated Universities (ORAU) assisting with characterization.

The history of Neely Research Center included the following:

- Supported GT research reactor operations
  - Spent fuel and source storage pool
  - Pneumatic lines
  - Hot cell used for dismantling and packaging fuel elements

- Encapsulation of high activity sources
    - Co-60, Cs-137, Cf-252, Sr-90, etc.
- GT Broad Scope Research Activities
    - High Activity Gamma and Neutron Sources

Following reactor dismantling, the GT Building showed significant signs of deterioration. The prolonged semiabandonment period between the reactor dismantling and the completion of decommissioning on-site had exacted a toll.

The building decommissioning was also complicated by the lack of alternative places to research activities still being managed inside the GT Building. Related to this, another complication was the involvement of several GT departments: this is to be expected when doing decommissioning within an active research center where interdepartmental research is the rule. State and local police involvement was significant, especially during the removal and transport of high-activity sources.

Approvals were granted by the Georgia Department of Nuclear Resources (GA DNR) and the Georgia Department of Transportation (GA DOT). In particular the involvement of GA DNR turned out to be slowing down activities, possibly due to the regulators' limited familiarity with decommissioning projects. Lack of familiarity often means overconservativeness.

A unique challenge was determining how to scan the building's storage pool. When the reactor was in operation, the source storage pool was used for cooling spent reactor fuel—in addition to other high-activity sources—and for keeping radiation levels below acceptable levels. Using a Trimble Spatial Station with a tracking prism (a laser scanner) ORAU Health Physics managed to produce georeferenced scan data, which were then used by ORAU Geographic Information System to map the collected data over a 3D graphics of the facility. The scan described the dimensions of the room and provided a precise illustration of where the contamination was located.

Decommissioning of the pool posed the following challenges:

- Pool characterization required the removal of 1-cm thickness of concrete.
- As the result of the evaporation and higher Cs-137 concentration, the pool water (some 16 m^3) had to be disposed of as radioactive waste.
- There was very fine silt left in the bottom of pool with a few cm of water, which had to be absorbed in ready mix concrete and turned into solid waste.
- Obtaining soil samples under the pool (part of the scoping survey) required access below 2 m of concrete (fortunately, no soil contamination was found and there was no need for environmental remediation).

Finally, demolishing the GT building was no easy task—workers must first cut through the concrete that encased a welded steel envelope. All included, the decommissioning project lasted from Oct. 2011 to Dec. 2012. In 2013 the site had been cleared and could be reused for other purposes.

1.4.4 Fuel Fabrication Plant, Bosco Marengo, Italy

The Bosco Marengo Fuel Fabrication Plant began operating in 1973. Until 1987, when Italy opted out of nuclear energy use, the plant had produced fuel elements for nuclear power plants in Italy and abroad. Following the closure of nuclear activities in Italy, the plant gradually converted operation to production of advanced ceramic materials such as for prostheses, porous components of fuel cells, cutting tools, etc. In 1995 all nuclear activities came to an end. In 2003 the operator applied for a decommissioning license. In 2005 SOGIN, as the national decommissioning and waste management operator, took over ownership [19].

At the time nuclear activities ceased, there were at Bosco Marengo 112 t of nuclear fuel, which were all shipped abroad. The last shipment took place in Nov. 2006.

In 2008 a decree was obtained for the dismantling of the plant, which was approved by the Ministry of Economic Development, on the advice of the Regulatory Body (ISPRA). Also in 2008 a contract was issued to start dismantling the plant; site activities started in Dec. 2008.

Between 2008 and 2010 decommissioning activities concerned the dismantling and (dry and wet) decontamination of the equipment previously used for fuel fabrication. The dismantling of the assembly line was completed in 2009; the decontamination of removed materials was completed in 2010. The demolition of the ventilation system and the liquid waste treatment systems was completed in 2013. In the same year 611 overpacks containing operational radioactive waste were refurbished.

The Bosco Marengo decommissioning activities are planned to end in 2017. By then the radioactive waste containers will be ready for transfer to the National Repository. Bosco Marengo will then be the first nuclear site in Italy to reach the state of unrestricted release.

In the meantime operational and decommissioning wastes are stored on-site, pending transfer to a new interim store being equipped to start operation in 2017. The 960-m^2 interim store has a capacity of 4080 m^3 of radioactive waste. By the end of 2014 there were 448 m^3 low- and intermediate-activity wastes stored at Bosco Marengo. In 2014 a mobile plant was installed for the processing of liquid waste and sludge.

As part of the decommissioning of the Bosco Marengo plant, SOGIN carried out in early 2016, in addition to radiological monitoring, the characterization of soil-subsoil and groundwater media. Some groundwater samples downstream from the plant exceeded the contamination threshold concentrations for chromium and other chemicals. However, it was proved the groundwater contamination was unrelated to plant activities but was due to industrial and agricultural activities in adjacent areas [26].

1.4.5 Bevatron, Lawrence Berkeley National Laboratory, United States

The Bevatron was built in the 1950s at the Berkeley's National Lab for a cost of $9 million (~$76 million 2012). It began operation in 1954, firstly as a proton accelerator. It was built to discover the antiproton (indeed discovered in 1955). Most of the information below is taken from Ref. [27].

In order to create antiprotons in collisions with nucleons in a stationary target while conserving both energy and momentum, the proton beam should have energy of approximately 6.2 GeV. At the time it was built, there was no way to confine a particle beam to a narrow aperture, so the beam space was about 4000 cm^2 in cross section.

The combination of beam aperture and energy required a 12,000-t iron magnet and a huge vacuum system. The accelerator had a diameter of about 60 m.

In the years following the antiproton discovery, much pioneering work was done here using beams of protons extracted from the accelerator proper, to hit targets and generate secondary beams, not only protons but also neutrons, pions (a pion is a particle having a mass approximately 270 times that of an electron), “strange particles,” and many others.

There was also a concrete shielding of 13,500 t. Initially the Bevatron was built with no shielding on top, but shielding was constructed later when the skyshine effect was detected.

The Bevatron occupied 12,000 m^2 of land. It used a significant amount of power, which was very expensive and eventually led to its closure. During its lifetime the Bevatron was converted from protons to a heavy ion accelerator for high-energy physics experiments; later on it was converted to a nuclear medicine treatment center. Finally Bevatron was shut down in 1993.

When the Bevatron was shut down the scientists, technicians, and engineers were reassigned to other tasks. They disbanded and no planning for decommissioning was made. The building sat idle for 15 years (1993–2008) while DOE pondered on what action should be taken for the facility.

Note that in general an extended postshutdown, no-action time is hardly conducive to successful decommissioning. First it causes the loss of knowledge (the “tacit knowledge” attached to individual memories and experience). Secondly it increases deterioration of structures, systems, and components, which will be more expensive to fix later. A deliberation of Berkeley City Council reads:

> *The Building 51 structure housing the Bevatron is deteriorating and consumes disproportionate maintenance resources. It does not meet current building codes, the roof leaks in several locations, and portions of the structure do not comply with current seismic design standards…The structure is seismically unsafe. Its demolition would provide a future safe working environment for an as—yet unidentified activity at Berkeley Lab.*
>
> *Ref. [28].*

Project Milestones are recapped in the following.

Isolate old utilities and establish reliable utilities. It is common practice in most decommissioning projects to discontinue the old electric systems and install new ones.

Remove shielding blocks. Some blocks were slightly activated (mostly from the early operation when Bevatron accelerated protons: as expected, heavy ions used later had much less penetration). Activated blocks were categorized as LLW.

Remove Bevatron accelerator. When the accelerator was removed, the interior of the building was then cleared.

Demolish the building structure. Retaining walls were reinforced. The building superstructure was preweakened before demolition. Eventually the superstructure was demolished in a controlled drop.

Remove foundations and slabs. This included removing the foundation system including pile/caisson caps, grade beams, shallow caissons, and facility floor; demolishing the deep tunnel; and removing the cooling tower basins. This process took over a year because they had to systematically manage the radiological hazards in the foundations and the soil. Therefore this project was not just decommissioning, but also environmental remediation.

Remediate soils and then backfill. For the Bevatron project a novel approach was used to document the probability of facility and site contamination; it is called hazards mapping. The activities conducted in producing a hazards map included the search of historical records and interviews with former personnel familiar with the facility. The historical documents included fire department reports, occurrence reports, chemical inventories, spill reports, lessons learned, radiological surveys, asbestos and lead inspection reports, and photos. It was also important to understand the accelerator operations that might have produced contamination. The interviews and records helped establish if there were any incidents that might have left residual contamination. This information was the input to derive hazard maps, which were plans of the facility with areas of suspected contamination. These hazard maps were provided to the characterization team to orient their predismantling investigations. The hazard maps were also provided to the demolishers to support on-the-job characterization efforts.

Much more radioactive material was found than expected initially. Lessons learned include the following: (1) it would have been advisable to have a single contact at the decommissioning organization who understood the release criteria and who clearly forwarded objectives to the offsite labs doing compliance measurements; (2) the lack of clearly defined minimum detectable concentrations resulted in offsite labs testing to stricter standards than needed and ultimately unnecessarily categorizing some materials as radioactive waste. The lack of these provisions impacted the remediation of shielding blocks, slabs, and foundations and cost an additional $10 million.

Tritium was a special case. Expected concentrations were based on the following:

- Activation generated mainly prior to 1974 (three half-lives)
- Significant amounts were not expected
- It was expected tritium be found *near* other activation products
- Tritium was expected to be found in soil and groundwater under *thin* floors

Instead tritium was found in unexpected places and concentrations such as the following:

- Under *thick* foundation slabs
- Was *not* under slabs with highest activation
- Levels were over 150 Bq/L (more than expected)
- Was *inconsistent* with expected equilibrium conditions

Possible (unconfirmed) sources of tritium contamination are the following:

- Accelerator cooling water spill/leak
- Migration from high activation to low activation areas due to groundwater flow

The demolition of the Bevatron began in 2009 and completed in early 2012. The cost was $47.6 M, 230,000 person-hours, and 1450 m^3 of soil cleanup.

The entire facility was demolished to complete the decommissioning, yielding more than 29,000 t of material that was then transported in over 1420 shipments to the Nevada National Security Site (NNSS) for disposal as LLW and mixed LLW. This material included over 750 concrete shield blocks, as well as pieces of the Bevatron itself, such as beamline pipes, enormous magnets, and other steel components.

The rainy season provided an additional challenge to the project. Rainfall for the city of Berkeley from November through March is heavy. As a result, nearly every piece of metal scrap and concrete rubble had to be packaged wet. A large quantity of an effective absorbent material that would meet the NNSS no-free-liquids disposal criteria was required.

1.5 Conclusions

The following conclusions can be extracted from the foregoing. Essential points are given more focus in following chapters.

Decommissioning policies and strategies change reflecting the discovery of new issues, growing experience, and national and international achievements. It is a task of the decommissioning practitioners to stay aligned with novelties and innovations in the field.

Transparent and adequate relations with all stakeholders are essential to the smooth progress of decommissioning. Identification of and interactions with the stakeholders should be considered earlier than the onset of a decommissioning project. In practice, anybody who claims the stakeholder's rights is indeed a stakeholder.

Early planning is vital to decommissioning success. This should be supported by competent and motivated teams. Participation of contractors in planning and execution of decommissioning is likely to be almost mandatory for all but the smallest projects, but it requires integration and harmonization of a culture often different from the operations staff's.

Real time assessment of decommissioning projects is crucial. In particular, this concerns ongoing expenditures and cash flow. Deviations from the planned schedule and budget should be identified and corrected as soon as possible. Uncertain and diverging costs undermine the credibility of the decommissioning industry.

Human factors need highest attention. This also includes "soft" factors such as motivation, leadership, team spirit, cross-cultural interactions, etc.

Early characterization of radioactive waste types and identification of waste management routes are essential in decommissioning planning. The lack of waste disposal facilities especially can delay the release of a decommissioning site, even though waste storage is an acceptable interim measure.

The importance of an effective and secure record management system throughout a facility's lifecycle and beyond is widely appreciated. This is part of the broader notion of KM, which may extend long after the end of decommissioning and includes not only the readability of records, but also the capability of using the information provided.

Feedback from decommissioning experience should be sought, assessed, and disseminated to all parties. The acquisition and reporting of lessons learned is of great assistance to the decommissioning team and should be fostered. Debates, seminars, and other international events are critical for sharing information among peers in this field.

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Part One

Planning

Safety and radiation protection

2

J. Kaulard
Private Consultant, Aachen, Germany

2.1 Introduction

Safety and radiation protection are of major concern for all involved in the decommissioning of facilities. During decommissioning the same overall safety and radiation protection goals need to be fulfilled as during operation of a facility, which are the following:

1. radioactive material is confined within the facility and is not uncontrolled released to the environment;
2. exposure of workers and public is kept below respective regulatory dose limits and is optimized beyond these limits to the extent practically possible ("kept ALARA"); and
3. in the case where fissile material in relevant quantities is present at the nuclear facility (e.g., at a nuclear power plant before removal of all spent fuel)
   - **a.** subcriticality is ensured; and/or
   - **b.** any residual heat is removed.

Safety primarily concerns the control of radiation sources (mainly goals 1 and 3) while radiation protection primarily focuses on the (potential) exposure of humans (mainly goals 1 and 2), but both safety and radiation protection are closely linked (especially with respect to goal 1).[1]

Already (Ref. [2], Chapter 9) provided important insights in aspects such as general concepts on safety and radiation protection, as important international and European regulations or as the core of a licensing process for decommissioning. And (Ref. [2], Chapter 9) clearly outlined that safety with respect to decommissioning is not limited to nuclear safety, as might be concluded from the above explanation, but safety-related to decommissioning also includes aspects of conventional safety that gain high importance.

Safety and radiation protection are addressed in the following paragraphs:

- Section 2.2: overview on changes in decommissioning-related international and European standards and on selected new international publications on related topics;
- Section 2.3: explanation on the planning for decommissioning and how safety assessment, planning for decommissioning, and risk management fit together;
- Section 2.4: explanation on how to systematically perform a safety assessment; and
- Section 2.5: outlook on future trends.

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[1] IAEA Safety Glossary—Terminology Used in Nuclear Safety and Radiation Protection, 2007 Edition [1]: "Protection and Safety—The protection of people against exposure to ionizing radiation or radioactive materials and the safety of radiation sources, including the means for achieving this, and the means for preventing accidents and for mitigating the consequences of accidents should they occur. Safety is primarily concerned with maintaining control over sources, whereas (radiation) protection is primarily concerned with controlling exposure to radiation and its effects. Clearly the two are closely connected: radiation protection (or radiological protection) is very much simpler if the source in question is under control, so safety necessarily contributes towards protection."

Advances and Innovations in Nuclear Decommissioning. http://dx.doi.org/10.1016/B978-0-08-101122-5.00002-8

2.2 International requirements, recommendations, and publications related to nuclear safety and radiation protection related to decommissioning

Within the last years some changes of requirements and recommendations on nuclear safety and radiation protection with respect to aspects of decommissioning occurred; in addition, several publications became available providing experience feedback and lessons learned related to decommissioning. The following is an overview on selected safety standards and experience feedback publications related to aspects of safety and radiation protection published or revised since 2012. The focus is on related activities by the International Atomic Energy Agency (IAEA),[2] the OECD Nuclear Energy Agency (OECD/NEA)[3], the European Union (EU)[4] (or its institutions), and the Western European Nuclear Regulators Association (WENRA).[5]

2.2.1 Safety

2.2.1.1 International Atomic Energy Agency

IAEA provides a system of requirements and recommendations related to decommissioning of facilities to support a safe and sound decommissioning. Table 2.1 provides an overview on decommissioning-related requirements and guidance documents of the IAEA Safety Standards Series. Some of the listed documents address general aspects of decommissioning (e.g., GSR Part 6) or are of general relevance for decommissioning (e.g., RS-G-1.7); some documents address aspects specific to dedicated facilities (e.g., fuel cycle facilities) and/or specific to individual life cycle phases (e.g., consideration of decommissioning aspects during construction of nuclear power plants, funding for decommissioning and dismantling during operation, and safety assessment for decommissioning) and thus are applicable during operation, during decommissioning, or both during operation and decommissioning.

Focusing on decommissioning specific developments completed since 2012, IAEA reviewed its former Safety Standards Series No. WS-R-5, "Decommissioning of Facilities Using Radioactive Material" [3], and published in 2014 the new IAEA Safety Standards Series No. GSR Part 6, "Decommissioning of Facilities" [4].

GSR Part 6 provides the general decommissioning requirements that shall be implemented in each IAEA Member State. The general requirements address such aspects as responsibilities associated with decommissioning, the management of decommissioning, the decommissioning strategy, financing of decommissioning, the planning

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[2] www.iaea.org.

[3] www.oecd-nea.org.

[4] http://ec.europa.eu/energy/en/topics/nuclear-energy.

[5] www.wenra.org.

Table 2.1 **Overview on decommissioning-related standards of the IAEA Safety Standards Series**

Safety Standards Series No.	Title	Published
GSR Part 4 (Rev. 1)	Safety Assessment for Facilities and Activities	Feb. 2016
GSR Part 6	Decommissioning of Facilities	Jul. 2014
NS-R-4	Safety of Research Reactors	Jul. 2005
NS-R-5 (Rev. 1)	Safety of Nuclear Fuel Cycle Facilities	May 2014
SSR-2/1 (Rev. 1)	Safety of Nuclear Power Plants: Design	Feb. 2016
RS-G-1.7	Application of the Concepts of Exclusion, Exemption and Clearance, Safety Guide	Aug. 2004
RS-G-1.10	Safety of Radiation Generators and Sealed Radioactive Sources	Dec. 2006
SSG-5	Safety of Conversion Facilities and Uranium Enrichment Facilities	Jun. 2005
SSG-6	Safety of Uranium Fuel Fabrication Facilities	Jun. 2005
SSG-15	Storage of Spent Nuclear Fuel	Mar. 2012
SSG-16	Establishing the Safety Infrastructure for a Nuclear Power Programme	Jan. 2012
SSG-22	Use of a Graded Approach in the Application of the Safety Requirements for Research Reactors	Nov. 2012
WS-G-2.1[a]	Decommissioning of Nuclear Power Plants and Research Reactors	Dec. 1999
WS-G-2.2[b]	Decommissioning of Medical, Industrial and Research Facilities	Dec. 1999
WS-G-2.4[a]	Decommissioning of Nuclear Fuel Cycle Facilities	Jun. 2001
WS-G-5.1	Release of Sites from Regulatory Control upon Termination of Practices	Nov. 2006
WS-G-5.2	Safety Assessment for the Decommissioning of Facilities Using Radioactive Material	Feb. 2009

[a] WS-G-2.1 and WS-G-2.4 are under revision and will be published as one combined new IAEA Safety Standards soon (IAEA draft safety standards DS 452, “Decommissioning of Nuclear Power Plants, Research Reactors and other Nuclear Fuel Cycle Facilities”).
[b] WS-G-2.2 is under revision and will be published soon (IAEA draft safety standards DS 403, “Decommissioning of Medical, Industrial and Research Facilities”).

and conduct of decommissioning, and the completion of decommissioning including termination aspects. Decommissioning is regarded to be a planned exposure situation as defined in IAEA Safety Standards Series GSR Part 3, “Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards” (BSS) [5], and the corresponding requirements of the BSS shall be applied (e.g., on dose limits for workers and for the public).

According to GSR Part 6, immediate dismantling and deferred dismantling or their combination are regarded as the only decommissioning strategies that shall be applied for each type of facility. The selected strategy shall become justified.

Immediate dismantling is the preferable decommissioning strategy.[6] Entombment, which was regarded a third strategy in WS-R-5 (1.5), and which is applied in some countries, now is "[…] not considered a decommissioning strategy and is not an option in the case of planned permanent shutdown. It may be considered a solution only under exceptional circumstances (e.g., following a severe accident)" (GSR Part 6, 1.10).

Following GSR Part 6 decommissioning and related safety considerations shall be addressed already during construction of a facility, resulting in the initial decommissioning plan. The extent of such safety considerations is different from that related to the final decommissioning plan, which shall be submitted to the regulatory body for approval before commencement of any decommissioning works; further details on IAEA's requirements and considerations on safety assessment are discussed in Section 2.4.

According to GSR Part 6 decommissioning of a facility includes the management of radioactive waste; as a consequence, it needs to be considered in the planning for and conducting of the decommissioning actions, and specific requirements from other IAEA Safety Standards shall be applied (e.g., Refs. [6,7]). Spent fuel (if any is on-site at the end of operation) should have been already removed at the start of decommissioning activities. However, in some cases spent fuel still is present when commencing decommissioning activities; in such a case the spent fuel has to be considered already in planning and has to be addressed in the safety assessment; also, IAEA requirements addressing spent fuel, for example, during operation of a nuclear power plant or of a research reactor shall be considered.

Recently, guides of the IAEA Safety Standards Series on decommissioning, especially No. WS-G-2.1 [8] and No. WS-G-2.4 [9], are under review and their publication is expected soon. In addition, a variety of publications in the IAEA series like Safety Reports Series, Technical Reports Series, TECDOC Series and Nuclear Energy Series are available providing experiences and lessons learned from IAEA Member States on the decommissioning of facilities. All these publications and information are available at the IAEA publication center (http://www-pub.iaea.org/books/).

It is important to note that the focus of the IAEA safety standards mentioned above is on the planning, conducting, and termination of decontamination and dismantling activities and the related safety assessments; aspects on waste management are addressed only to the extent that waste management can affect decontamination and dismantling activities and the logistics (including build-up of radiation sources), except for aspects on clearance, which are addressed in RS-G-1.7 [20]. Specific requirements and recommendations related to the treatment, transport, and storage of radioactive waste are subject to separate IAEA safety standards not discussed in this chapter.

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[6] In this context it is worth referring to IAEA TECDOCs Series No. 1478, "Selection of decommissioning strategies: Issues and factors," which provides examples in which the application of deferred dismantling can be regarded acceptable because immediate dismantling is impossible (e.g., in the case of a lack of funding); however, deferred dismantling in general is not the preferable decommissioning strategy.

2.2.1.2 OECD Nuclear Energy Agency

In support of its member countries the OECD/NEA has issued, since 2012, several publications on aspects of decommissioning of facilities. These publications address mainly cost estimation for decommissioning (refer to Chapter 5), and some of them also address aspects of remediation of buildings and associated land, which is not discussed in this chapter. In 2012 OECD/NEA published its report on the management of large components from decommissioning to storage and disposal [10], addressing experiences on the removal and dismantling of large components and by this reflecting a trend in decommissioning.

2.2.1.3 European Union

In 2014 the European Union amended its council directive on the nuclear safety of nuclear installations from 2009 [11] to incorporate lessons learned from the Fukushima Daiichi accident of 2011 [12]. In addition, Ref. [12] covers now all phases of the life cycle of a facility, including decommissioning. As such, European facilities under decommissioning are affected by the directive, although not all requirements hold for such facilities; for example, the requirements for a periodic review of the nuclear safety are not applicable to facilities under decommissioning. Following the European mechanism on regulations, the amended council directive shall be implemented in the national regulations of the European countries by mid-2017.

2.2.1.4 Western European Nuclear Regulators Association

The decommissioning-related requirements (safety reference levels) of WENRA serve to stipulate a harmonized high level of nuclear safety among the European countries. Their implementation in the national regulatory systems takes place within the full responsibility of the individual WENRA member countries. As of Jun. 2016 WENRA has published safety reference levels on the operation of nuclear power plants, on the decommissioning of facilities, on the storage of radioactive waste and spent fuel, and on the disposal of radioactive waste.

The latest version, 2.2, of WENRA Report Decommissioning Safety References Levels [13] was published in 2015. In this report, 62 safety reference levels address safety management, decommissioning strategy and planning, conduct of decommissioning, and safety verification. The safety reference levels are mainly based on IAEA safety standards, especially on WS-R-5 [3], and on WENRA's experiences in decommissioning. IAEA requirements were evaluated by WENRA and those of highest importance for decommissioning practice from WENRA's point of view became safety reference levels. As such the safety reference levels do not address all aspects of safety during decommissioning (as the IAEA safety standards do) but only those that are regarded to be the most important ones. Aspects on radiation protection are mainly not addressed because they are already subject to a binding European regulation (new EU BSS [14]). According to WENRA an initial decommissioning plan has to be submitted to the regulatory body "in support of the licence application for construction for a new facility" (Ref. [13], DE-20). This decommissioning plan and subsequent versions have to be reviewed periodically during operation of the facility, typical in parallel to the periodic safety review (PSR) performed for facilities during operation. A final decommissioning plan has to be submitted to the regulatory body within two years after final shutdown. The decommissioning plan has to be supported by an appropriate safety assessment, in case of the final decommissioning plan by a safety case. During decommissioning the safety case should be reviewed "at major steps in the decommissioning project and when changes of the decommissioning plan are intended or changes of regulatory requirements or other safety relevant information arise to ensure the safety case is still valid and appropriate to support the safe conduct of the decommissioning work" (Ref. [13], DE-54). In addition, a review has to be performed on a regular basis with a periodicity set by the regulatory body.

It is important to note that some of the safety reference levels for the storage of radioactive waste (and spent fuel) [15] are also relevant for decommissioning projects when radioactive waste will be stored in the facility or the construction of a storage facility is part of the project.

When comparing standards of the IAEA Safety Standards Series with the WENRA Report Decommissioning Safety Reference Levels [13], it is important to note that within the WENRA decommissioning safety reference levels a combination of the concept of the safety case (used in several countries worldwide) and of IAEA's concept of a final decommissioning plan [4,8] was used. In the combination the safety case is "a collection of arguments and evidence in support of the safety of a facility or activity." ([13], glossary), while the final decommissioning plan is a "final document … with detailed information about the concept and schedule for the decommissioning and dismantling of the nuclear facility" ([13], glossary); in other words, the safety-related elements of IAEA's final decommissioning plan are not part of the WENRA's final decommissioning plan but form WENRA's safety case.

2.2.2 Radiation protection

In 2007 the International Commission on Radiological Protection published its latest general recommendations on radiation protection, ICRP 103 [16]. Significant changes compared to the previous ICRP recommendations of 1990, ICRP 60 [17], are proposed; for example a new concept on exposure situations (planned, existing, and emergency) is introduced and the consideration of ionizing radiation due to naturally occurring material is improved; the proposed dose limits remain unchanged compared to ICRP 60 but a new concept of dose constraints below the dose limits was introduced. As a consequence, these new recommendations stimulated the review and revision of existing international requirements on radiation protection that were based on the former ICRP 60, especially IAEA's Basis Safety Standards [19] and the Basic Safety Standards of the European Union [18].

With respect to the format of this book, not a full overview on all changes in IAEA's and EU's BSS can be given. Instead, in the following paragraphs those modifications at IAEA's and EU's BSS are briefly addressed that are regarded most important for the decommissioning of facilities.

2.2.2.1 International Atomic Energy Agency

In 2014 IAEA replaced its Safety Series No. 115, “International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources” [19], with the new IAEA Safety Standard Series GSR Part 3, “Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards” [5].[7] The new GSR Part 3 addresses in mainly four chapters general requirements on radiation protection, requirements specific to planned exposure situations, requirements specific to emergency exposure situations, and requirements specific to existing exposure situations. For the three exposure situations the exposure of workers and the public is addressed; in case of the planned exposure situation, medical exposure is also addressed. The dose limits for workers and the public remain unchanged with respect to Ref. [19] except for the dose limit of the eye which was lowered to 20 mSv/a; the following ICRP 103 dose constraints are introduced: “[…] Dose constraints are applied to occupational exposure and to public exposure in planned exposure situations. Dose constraints are set separately for each source under control and they serve as boundary conditions in defining the range of options for the purposes of optimization of protection and safety. Dose constraints are not dose limits […]” (Refs. [4,5], 1.22). The exemption limits of Ref. [19] for moderate amounts of material are kept and are supplemented by the activity concentration limits for exemption or clearance of large amounts of material, as defined in IAEA Safety Standards Series No. RS-G-1.7 [20], which gain higher binding character.

Although compared to the operation of facilities (especially in the case of nuclear power plants) of less relevance, aspects of emergency preparedness might play a role in decommissioning, at least when spent fuel is at the facility when decommissioning will commence. Therefore, it should be noted that the new IAEA Safety Standards Series No. GSR Part 7, “Preparedness and Response for a Nuclear or Radiological Emergency” [21], which converse general requirements related to emergency preparedness, was published in 2015.

2.2.2.2 European Union

At the end of 2013 the European Union published it’s new “Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom” [14]. It replaces its precursor, “Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation” [18], as well as four further council directives related to aspects of radiation protection (Council Directive 89/618/EURATOM, Council Directive 90/641/EURATOM, Council Directive 97/43/EURATOM, Council Directive 2003/122/EURATOM). This new EU BSS [14] shall become

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[7] An interim version of GSR Part 3 was already published in 2011.

implemented in the national regulatory systems by the EU Member States by Feb. 8, 2018 at the latest.

The development of the new council directive [14] was based on its precursor [18] and those mentioned four council directives, and it took into account, among others, the Ref. [16]. Recommendations [16] and the activity concentration related clearance and exemption levels for bulk material as defined within IAEA Safety Standards Series RS-G-1.7 [20].

The most relevant change within the new EU BSS [14] from a decommissioning point of view is related to the new activity concentration related clearance levels (for unrestricted release) for bulk material, taken from Ref. [20]. They are for several radionuclides lower than those levels that could be derived from the requirements in the past EU BSS [18]. This will result in lower amounts of material, which can be released unrestrictedly, than in the past and will accordingly increase that material, which can only be released with restrictions.

Other changes may have the following effects:

- they may affect the organization of the radiation protection, because the EU BSS introduces two roles: the radiation protection expert (RPE) and the radiation protection officer (RPO). According to Ref. [14] (p. 73) the “radiation protection expert means an individual or […] having the knowledge, training, and experience needed to give radiation protection advice in order to ensure the effective protection of individuals, fand whose competence in this respect is recognized by the competent authority”; the “radiation protection officer means an individual who is technically competent in radiation protection matters relevant for a given type of practice to supervise or perform the implementation of the radiation protection arrangements.” Whether these two roles will affect the radiation protection organization of a facility strongly depends on the current national regulatory system and on the implementation of the new EU BSS in the national system; or
- they may affect the maximum acceptable level for effluents of radioactive material with air and water for a facility: in future contributions effluents from NORM (Naturally Occurring Radioactive Materials) industries (if any are located in the vicinity of the facility) also need to be considered when calculating the potential exposure of the public due to effluents from a facility; this might result in lower maximum acceptable levels than in the past.

The new EU BSS requires in future implementation of the concept of dose constraints, proposed in ICRP 103 [16], for the public being the same as those for workers. The details of the implementation are subject to the EU Member States’ discretion; accordingly potential consequences for the decommissioning of facilities are difficult to predict. Because the use of dose constraints is well known in the nuclear industry as one of several tools and concepts within occupational radiation protection, implementing ALARA-significant consequences for occupational radiation protection is not to be expected.[8]

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[8] Some practical information on the current use of dose constraints within the optimization of occupational exposure can be found in a report of the Expert Group on Occupational Exposure of the CRPPH of OECD/NEA [22].

2.3 Planning for decommissioning[9]

2.3.1 Initial planning for decommissioning

Planning for decommissioning starts when a facility is being designed, in other words, typically 60 years before commencing of the first decommissioning activity for a nuclear power plant. Following international requirements, for example, IAEA's GSR Part 6 [4] or WENRA's Decommissioning Safety Reference Levels [13], and as required in several national regulatory systems, initial planning for decommissioning comprises the development of an initial decommissioning plan. This initial decommissioning plan has the following main purposes:

- to give an outline on a potential final end state and on the decommissioning strategies to achieve the end state;
- to provide confidence that decommissioning activities to achieve the final end state are feasible (e.g., by providing technical studies) and can be done safely (e.g., by use of proven technologies); and
- to summarize the expected (radioactive) wastes generated during decommissioning, to provide estimations on their quantities, and to outline their disposal routes.

The initial decommissioning plan also forms the basis for cost estimations for a later decommissioning and disposal of radioactive waste. Accordingly, the level of detail needs to be adequate (for further details refer to Chapter 5). The initial decommissioning plan has to be submitted to the regulatory body when applying for the authorization to operate the facility.

Obviously, safety consideration is part of the development of the initial decommissioning plan. The level of detail of such safety consideration should be in line with the type and complexity of the facility. Due to the overview character of the technical elements in the initial decommissioning plan, such safety consideration will mainly focus on questioning whether current radiation protection requirements for the workers and for the public can be fulfilled during the future decommissioning.

Not obvious is the need for risk management to be in place for the initial decommissioning plan. Such a risk management can contribute to ensuring that the initial decommissioning plan remains valid and can become concretized and implemented in the future. How such a risk management plan might look like was addressed in IAEA's project, "Decommissioning Risk Management" (DRiMa project), which was completed at the end of 2015 and for which a report is under preparation and shall be published in 2017. Preliminary results were presented at IAEA's "International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes" [23]: an initial decommissioning plan is based on assumptions, for example, related to the expected end of operation or to the facility status at the end of operation, on the possible final end state of

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[9] Safety consideration and safety assessment address both aspects of safety and radiation protection, as explained in Section 2.1. Accordingly, the correct phrasing would be "safety and radiation protection consideration" and "safety and radiation protection assessment." However, following international terminology, the use of "safety consideration" and "safety assessment" is used further on in this section.

decommissioning, or on available disposal routes. Such assumptions may change or may be uncertain with regard to their reliability in future years; if they change or become invalid the initial decommissioning plan may also become invalid. The DRiMa project proposes to monitor these assumptions with a kind of "light" risk management called assumption management. The assumptions become identified, are recorded in an assumption register, and are monitored regularly. Depending on the monitoring results assumptions may become changed, replaced, and/or the initial decommissioning plan becomes revised.

Preparation of the initial decommissioning plan will result not only in the initial decommissioning plan, but also in a better understanding on what is needed to successfully decommission the facility in the far future and what is yet missing, for example,

- which techniques are needed, that are not yet available, for decontamination and dismantling and therefore require research and development;
- which operational systems are needed for decommissioning and should be subject to long-term aging management because they are difficult or impossible to replace during decommissioning; and
- which radioactive waste routes need to be established in the future and therefore require attention and actions.

Initial planning for decommissioning during designing and construction of a facility is not limited to the preparation of the initial decommissioning plan. Among other actions it includes the start of the collection of information needed for a future decommissioning. This includes an early identification of decommissioning-relevant information that needs to be recorded during the life cycle of the facility. IAEA's technical reports [24,25] provide advice on which information to collect.

Initial planning for decommissioning includes also considering technical aspects in the facility design, which facilitates a future decommissioning. IAEA and OECD/NEA published in 2010 and 2011 technical reports [26,27] in which decommissioning-related design aspects are discussed; the technical reports are based on lessons learned from past decommissioning projects. Such aspects include sufficient space and openings for large component removal and transfer through the facility or the use of material, which has a lower cross section for neutron activation, to support the minimization of the exposure of workers. Very often, such aspects are already advisable for operation of the facility, like replacement of large components in the context of operational lifetime optimization or ensuring low radiation levels to keep the exposure of the workers low during maintenance.

As mentioned previously, the initial decommissioning plan forms the base for cost estimates for decommissioning and waste management. Accordingly, the initial planning for decommissioning includes the estimate of the future costs for decommissioning activities and waste management, including the final disposal. In addition, the initial planning needs to determine the funding mechanism to collect the needed financial resources during operation of a facility and to define the monitoring of the funds generated over time. More details on aspects on cost estimates and funding can be found in Chapter 5.

2.3.2 Ongoing planning for decommissioning

During operation of a facility the (initial) decommissioning plan needs to be reviewed periodically and revised depending on the review outcome. This is to keep the (initial) decommissioning plan valid and to ensure that decommissioning of the facility is still possible and funding is based on reliable information. A typical periodicity of the review is that of the PSR to systematically reassess the current safety of the operational facility; very often the (initial) decommissioning plan will be reassessed in parallel to conducting such a PSR.

In addition, a revision of the (initial) decommissioning plan might be necessary if, among others, changes of the facility or of the regulatory requirements occur. In that sense, the previously mentioned assumption management may also initiate changes of the initial decommissioning plan. Other aspects potentially initiating a revision of the (initial) decommissioning plan are experiences from other decommissioning projects or technological developments (e.g., new technologies arrive at the market, old technologies disappear).

In some countries the (initial) decommissioning plan has to be continuously improved towards the final decommissioning plan. Over the decades, the maturity of the former initial decommissioning plan improves and evolves towards that of the final decommissioning plan. A major argument in favor of this approach is that a final decommissioning plan is instantaneously available when a facility is shut down; at the same time technical details are elaborated sufficiently in advance of the final shutdown, improving the base for cost estimates and reducing uncertainties. Alternatively and as a practice in some countries, the level of maturity of the final decommissioning plan remains unchanged over a long time 5 to 10 years before planned final shutdown, the development of the final decommissioning plan starts. An advantage of this approach is that recent developments (e.g., on the facility status, on the available waste disposal routes) or changed/new safety requirements and regulatory criteria can be more easily integrated into the final decommissioning plan without rejecting significant work previously made. Independent from the approach followed, it is a must to be able to submit a final decommissioning plan to the regulatory body for approval soon after final shutdown of the facility (or in the timeframe set by the regulatory system).

In case the preparation of the initial decommissioning plan (or the assumption management) revealed the need for further developments (e.g., technologies, radioactive waste disposal routes), tracking of such developments belongs to the ongoing planning for decommissioning. This contributes to ensuring that the conditions for a successful decommissioning are in place when decommissioning is intended to start. Tracking may also include an active participation in research and development.

2.3.3 Final planning for decommissioning

The final planning for decommissioning serves to prepare the decommissioning of the facility such that it can start after approval by the regulatory body. Important objectives of the final planning for decommissioning are the following:

- to define the objectives of the decommissioning, including strategy and final end state;
- to define the decommissioning activities and waste management strategies and to define the structure on how the activities will be performed;

- to prepare the final decommissioning plan in support of getting an approval by the regulatory body to start decommissioning; and
- to set up the decommissioning organization and to prepare the working documents for the first decommissioning activities to be started after approval by the regulatory body on the basis of the final decommissioning plan.

If relying on the initial and ongoing planning for decommissioning at start of the final planning for decommissioning, a review of the (initial) decommissioning plan and its assumptions in light, for example, of the status of the facility and of current safety requirements and regulatory criteria should be made to ensure that they still are valid and reliable. This holds especially true for the decisions on the decommissioning strategy and for the final end state of the decommissioning. The (initial) decommissioning plan typically sketches the sequence of the main decommissioning activities on a high level. If regarded to be still valid, these activities need to become concretized now to a level allowing the regulatory body to approve decommissioning.

As mentioned already in Section 2.2 according to international consensus [4] immediate dismantling and deferred dismantling are the two main decommissioning strategies. In practice, a combination of both strategies is often applied, in which large components of a facility are removed (immediately) and temporarily stored on-site or off-site for a period, in which radioactive material significantly can decay to improve the radiological conditions for their deferred dismantling and/or to enable the clearance of material. After that period the components will be dismantled and decontaminated (deferred dismantling). In addition to the radiological or waste management aspects, the removal of large components may also shorten the overall duration of the decommissioning project compared to an in situ dismantling and thus may be advantageous from a cost point of view.

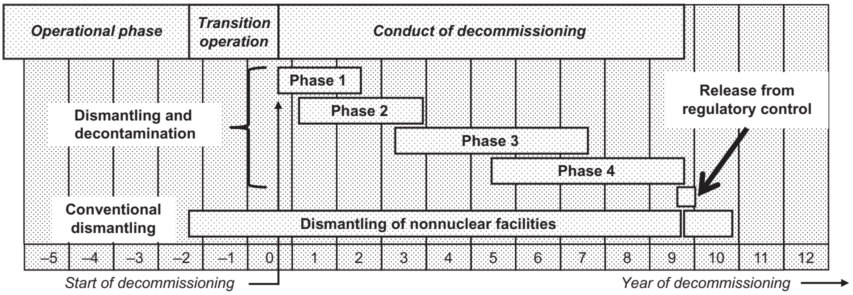
In many countries the final end state will be the unrestricted release of the remaining buildings and the associated land; in some countries, a restricted release of the facility buildings and/or of the associated land might also be possible. However, in the past preparation for and release of buildings and of associated land was considered as last (or at least as one of the last) activities in a decommissioning project. Recent examples show that a release of some buildings and of some part of the associated land is already possible while the decommissioning is still ongoing; such an approach might be favorable to reduce costs for decommissioning (e.g., because fewer buildings are subject to maintenance anymore). Such an early release is possible, if the buildings and the part of the associated land are no longer needed for the further decommissioning (e.g., no structures, systems, or components needed for the further decommissioning are located in the buildings/at the land, or buildings/land are not needed for storing radioactive waste); in addition the buildings and the associated land shall not be affected by the further decommissioning activities (e.g., by radioactive effluents, direct exposure from radioactive waste) because they will become public areas with respect to radiation protection. Such a stepwise release of buildings and associated land will result in the same final end state for decommissioning as when releasing all buildings and the associated land at the end of the decommissioning activities. But to optimize the benefit of that approach it should be integrated in the planning of the decommissioning activities at an early planning stage; this ensures that decommissioning activities are performed first in those buildings/at the part of the associated land intended for early release and that the radiological was well as the nonradiological conditions (e.g., replacement of systems) for release are established effectively and in time.

For large and complex facilities the decommissioning activities may be grouped in phases (multiple-phase approach); an example for a recent German decommissioning project is given in Fig. 2.1 in which the decommissioning activities are grouped in four phases. Depending on the national regulatory system, phases may require separate approvals by the regulatory body. If a multiple-phase approach is applied a clear description of the decommissioning activities for each phase is needed; moreover, the start point and the end point of each phase have to be defined clearly to ensure a clear link between previous and succeeding phases. In addition, emphasis has to be given to the investigation of the interdependencies between different phases.

The multiple-phase approach offers the advantage of providing detailed documents and information only for the phase for which an approval is requested, while for the remaining later (future) phases a less detailed outlook is given. This outlook should allow the regulatory body to assess the overall safety of all decommissioning activities (including the impact on the public) and the overall waste management; it shall allow the regulatory body to understand the impact of the phase, for which an approval is requested, on the later (future) phases. By doing so, the complex structure of the decommissioning activities becomes reduced and first decommissioning activities (related to the first phase) can start early after final shutdown, while for the later (future) phases missing relevant data and information still can be generated without preventing the start of decommissioning. In addition, new information emerging from current phases can be incorporated into later phases. As such, the multiple-phase approach can help in reducing delays in the conduct of a decommissioning project, and it supports safety and radiation protection because experiences from past or current phases can be incorporated into the planning of future phases.

As mentioned previously, the use of a multiple-phase approach can be useful for the large and complex decommissioning. However, the effort to execute a multiple-phase approach should not be underestimated; the need to precisely define start and end point for each phase (and ensure consistency accordingly) and to submit specific documentations (e.g., updates of the final decommissioning plan) for each phase will introduce addition work. In addition, in some national regulatory systems a formal stakeholder involvement process is intended for each approval (i.e., for each phase), which might delay the approval process. Accordingly, the advantages and disadvantages of the multiple-phase approach should be carefully assessed and balanced—in case of well known types of large facilities and depending on the decommissioning-related experience of the operator, a practical approach is to keep the number of phases small, for example, two phases for a pressurized water reactor (PWR) with the first phase on all components except for the reactor pressure vessel, which is subject of the second phase.

The waste management concept covered by the initial decommissioning plan needs at least a detailed analysis and further concretization. It needs to consider among others updated data on the facility's materials (radioactive waste, conventional hazardous



Transition operation	Phase after final shut down and before formal start of decommissioning activities, including • removal of spent fuel • system decontamination • removal and disposal of radioactive media generated during operation
Phase 1	First dismantling of contaminated components to generate free space for the later dismantling activities, including • equipment airlock and air-recirculation system (modification/replacement) • flooding tanks • external parts of the control rod guide thimbles and drives • accumulator In parallel: set up of infrastructure needed for later dismantling activities
Phase 2	Dismantling of large components, including • pipes and main coolant pumps of the primary coolant loops • steam generators
Phase 3	Dismantling of activated structures, systems and components, including • reactor vessel internals • reactor vessel • biological shielding • concrete cross beams • rack from the former spent fuel pool
Phase 4	Dismantling of remaining systems and components • crane • refuelling platform • ventilation system • water treatment facility
Release from regulatory control	Clearance of the buildings and of the associated land (subject to nuclear regulations)
Afterwards	Conventional demolition or reuse of the buildings (formerly subject to nuclear regulations)
In parallel to transition operation and phases 1–4	Conventional dismantling of nonnuclear facilities (e.g., buildings of administration) which never were subject to a nuclear regulations

Fig. 2.1 Example of a multiple-phase approach for a German pressurized water reactor (PWR). Based on EON 2003, EON Kernkraft GmbH; Kurzbeschreibung für den Abbau des Kernkraftwerks Stade; 2003; J. Kaulard, B. Brendebach, Radiation protection during decommissioning of nuclear facilities—experiences and challenges. Contribution at 13th International Congress of the International Radiation Protection Association (IRPA), Glasgow on 14–18 May 2012; UM. Niedersaechsisches Umweltministerium, Genehmigungsbescheid für das Kernkraftwerk Stade (KKS) (Bescheid 1/2005), Internet version of the first license for decommissioning; 2005.

waste, materials to be cleared), existing related regulatory requirements, and existing or necessary new infrastructure. In case a national disposal facility for radioactive waste originating from decommissioning is not available, an immediate dismantling of a facility is still possible, when it is foreseen to store the radioactive waste in interim storage facilities. Moreover, if the commencement date of a disposal facility is difficult to predict or if the annual processing capacity of a disposal facility is significantly low compared to the annual quantity of generated conditioned radioactive waste the use of an interim storage facility might be favorable also. In such a case or in the case of a missing national disposal facility the use of interim storage facilities will allow an early start of a decommissioning project and will keep the decommissioning project proceeding smoothly and will support transformation of the complex decommissioning of the facility into a more simple management of radioactive waste, which is stored in the interim storage facility.

A major element in the final planning for decommissioning is the preparation of the final decommissioning plan and of supporting documents (according to IAEA terminology, [1]). The final decommissioning plan (and supporting document) forms the base for the regulatory body's approval of the decommissioning of a facility. The format and content of the final decommissioning plan and the supporting documents depend on the national regulatory system and the regulatory body's need to form its opinion on the decommissioning activities. Typically a strong focus is laid on the final end state for decommissioning, on the demonstration of safety (including statements on effluents and the exposure of workers and the public), and on waste management (including clearance, if an option in the country) and related disposal routes. In general, the final decommissioning plan and the supporting documents describe the decommissioning on such a level that serves for the regulatory body to approve (or not approve) the decommissioning activities, but which needs much more concretization and detailed planning to enable the implementation of the decommissioning activities on the work level. As such, the level of detail of a final decommissioning plan is less detailed than what is needed for the implementation of the decommissioning activities. The concretization and detailed planning of the final decommissioning plan is subject to the implementation process for decommissioning and is supervised by the regulatory body on grounds of the approved final decommissioning plan (and supporting documents); accordingly, an approved final decommissioning plan spans the frame in which the implementation will take place and which the implementation is not allowed to leave.

An international consensus on what should be addressed in the final decommissioning plan and its supporting documents is formulated in recent IAEA safety standards, such as GSR Part 6 [4] or the WS-G-2.4 [9], which is currently under revision. According to GSR Part 6 (requirement 11, 7.10) the main elements of the final decommissioning plan and its supporting documents shall address "the selected decommissioning strategy; the schedule, type and sequence of decommissioning actions; the waste management strategy applied, including clearance, the proposed end state and how the licensee will demonstrate that the end state has been achieved; the storage and disposal of the waste from decommissioning; the timeframe for decommissioning; and financing for the completion of decommissioning." As a consequence the final decommissioning plan and its supporting documents need to provide information such as the following (Ref. [9], 5.12):

(a) A description of the […] facility, the site and the surrounding area that could affect, and be affected by its decommissioning;

(b) The life history of the facility, reasons for taking it out of service, and the planned use of the site during and after decommissioning;
(c) Information on incidents that have occurred during the operational phase, in particular those involving spills and the release of radioactive material;
(d) Details of significant modifications carried out during the operational phase;
(e) An assessment of the amount, type and location of residual radioactive and hazardous non-radioactive materials in the facility, including calculational methods and measurements to determine the inventories (i.e., the characterization of the facility);
(f) A description of the regulatory framework within which decommissioning will be carried out;
(g) A description of the proposed decommissioning activities, and the program, including a detailed schedule;
(h) The rationale for selecting the preferred decommissioning option;
(i) Descriptions of safety assessments and environmental impact assessments, including the potential radiological and nonradiological hazards to the workers, the public and the environment;
(j) A description of the proposed environmental monitoring program to be undertaken during decommissioning;
(k) A description of the experience, resources, and responsibilities of the decommissioning organization, including details of the qualifications, skills, and training of the decommissioning personnel;
(l) A statement of the availability of any specific management, engineering, and decommissioning techniques;
(m) A description of the proposed strategy for waste management;
(n) A description of the proposed programs for radiation protection and safety to be used during decommissioning;
(o) A description of the criticality control program, if necessary;
(p) A description of the quality assurance program;
(q) A description of the measurement program, equipment, and methods to be used to verify that the site will comply with the release requirements;
(r) A demonstration of the adequacy of the financial mechanism for ensuring that decommissioning, including waste management, will be carried out in a safe manner;
(s) A description of the organizational and administrative controls;
(t) A description of other applicable important technical and administrative considerations such as safeguards, physical protection arrangements and details of emergency preparedness.

Recommendations on the format and details of the final decommissioning plan and its supporting documents can be found in the IAEA Safety Report Series No. 45, "Standard Format and Content for Safety Related Decommissioning Documents" [28].

In the case of a multiple-phase approach a final decommissioning plan (e.g., Fig. 2.1) should be prepared for each phase. In general, format and content could be as described above. However, from a practical point of view, some deviations might be useful:

- Format and content of the final decommissioning plan for the first phase should be as described above and should be prepared for the decommissioning activities related to that first phase.

  In addition, the final decommissioning plan needs to contain an overview on the overall decommissioning activities including, among others, the schedule, descriptions on the individual phases with their main decommissioning activities and with their start and end point; the overall waste management concept; and the concept of operation of residual structures, systems, and components during the overall decommissioning. Such an overview is needed, among other reasons,

  - to understand the overall decommissioning and how to arrive at the final end state;
  - to determine if the individual phases fit together and do not interfere with each other (or do partially prevent them);
  - to assess the safety of the overall decommissioning activities.

  The final decommissioning plan for the first phase needs to also provide the results of a safety assessment on the overall decommissioning activities (overarching safety assessment). Accordingly, the level of detail of the description of the overall decommissioning activities related to that of the individual phases has to be such that the conduct of that overarching safety assessment with conservative results is possible.

- The format and content of the final decommissioning plan for any further phase could from a pragmatic point of view be reduced to the information (and chapters) that is specific to the phase. For example, a summary of the facility is no longer needed; the same is true for the description of the proposed strategy for waste management. In this case, such general aspects described in the final decommissioning plan for the first phase will be changed, and the changes need to be described and reflected in the related safety assessment. This holds true especially if the overall decommissioning activities will be changed (e.g., due to new information emerging from previous phases).

The final planning for decommissioning requires significant effort to collect relevant input data, which influences the operator's decision making on aspects such as the final end state of decommissioning, the decommissioning strategy, the application of a multiple-phase approach, and the waste management concept. The characterization of the facility plays an important role in the collection process; this includes the characterization of the radiological inventory (radiological characterization) as well as the inventory of other nonradioactive, hazardous material (e.g., asbestos, polychlorinated biphenyls) because they can significantly influence the sequence and structure of work and the conventional waste management.

In the case partial or full system decontaminations are foreseen (e.g., to improve the radiological conditions for workers or to improve material clearance), it is advisable to perform the radiological characterization to its fullest extent after the full system decontamination of the systems to reflect the actual starting point for decommissioning; if the system decontamination is foreseen as part of the decommissioning activities, the radiological characterization has to be performed before that decontamination to provide input on, for example, the safety assessment related to the final decommissioning plan; in such a case, new and more detailed radiological data should be retrieved after the decontamination but before detailed planning of the individual steps, for example, for worker's safety reasons or for use for waste characterization.

The radiological characterization for the final planning for decommissioning serves mainly to estimate the amount of radioactive waste and to identify the main radioactive waste categories, to estimate the exposure of workers and the public during normal decommissioning operation same and for accident situations, and to support designing the decommissioning phases and steps within a phase. It is worth mentioning that the level of detail of the radiological characterization for the final decommissioning plan and its supporting documents needs not to be as such needed for developing work instructions or for fulfilling waste acceptance criteria—for these objectives, more detailed characterizations will be performed in the context of the detailed work planning and as part the waste management processes executed during decommissioning.

Other important contributors to the information collection are the analysis of documentation from construction and operation of the facility (including modifications during operation) same as careful facility inspections (e.g., site walk downs) and interviews with staff (including retired staff), to ensure that documentation complies with the real facility layout.

The final planning of the decommissioning involves not only conducting a safety assessment (refer to Section 2.4), but also a risk management process. When a first plan on the decommissioning activities exists, a safety assessment is performed; if that safety assessment does not confirm safety, the decommissioning activities need to be modified and the safety assessment shall be repeated. Modification of the decommissioning activities and repetition of the safety assessment will continue until safety is verified. Latest for that version of the decommissioning activities a risk management process should be performed.[10] The objective is to identify risks (threats or opportunities) which may impact the success of the decommissioning and to set up a monitoring and control system. In case of unacceptable threats (either due to their impact or frequency of occurrence or both) or opportunities, which are worth incorporating in the planned decommissioning activities, the planned decommissioning activities need to be modified and the risk assessment process will be repeated. Similar to the safety assessment process modification of the planned decommissioning activities and repetition of the risk management process will continue until the remaining risks are regarded as acceptable. Whenever the planned decommissioning activities become modified, the impact of the modifications on safety or on the remaining risk needs to be assessed by a safety assessment or a risk assessment. As such, the planning process and the associated safety assessment and risk management form three iterative processes that are closely linked.

During the risk management a risk register will be populated, which will be used during the later conducting of the decommissioning activities. The risk register is one element in a standard risk management process (e.g., according to ISO 31000:2009 [29]). It is an instrument to systematically record all risks identified, to document the related treatment strategies like risk avoidance or risk transfer, and to systematically monitor and review the identified risks during decommissioning. In the previously mentioned IAEA DRiMa Project, a specific risk register was developed to support an easy to use risk management specific for decommissioning. In addition, a prompter list (risk families) was developed to systematically analyze the decommissioning activities/the related decommissioning project to identify risks and to evaluate their impact and occurrence frequency.

2.4 Safety assessments for decommissioning[11]

In Section 2.3, information about the decommissioning plan was given. Among other needs, the need for safety considerations supporting the initial decommis-

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[10] It is advisable, to perform already a risk assessment (as the central part of a risk management process) for the first plan on the decommissioning activities in parallel to the safety assessment and for subsequent updates of that plan to enable an early feedback with regards to risks related to the plan.

[11] Safety consideration and safety assessment address both aspects of safety and radiation protection, as explained in Section 2.1. Accordingly, the correct phrasing would be “safety and radiation protection consideration” and “safety and radiation protection assessment.” However, following international terminology, “safety consideration” and “safety assessment” are used further on in this section.

sioning plan and for safety assessments supporting the final decommissioning plan was mentioned.

With respect to the final decommissioning plan the safety assessment serves to do the following:

- to demonstrate that the decommissioning activities described in the final decommissioning plan can be conducted safely while—to the extent necessary—taking into account administrative and engineered safety measures; and
- to provide input for the detailed planning on how to ensure safety during implementation of the decommissioning activities.

Whether a decommissioning activity can be regarded safe depends on whether its normal (planned) conduct and any consequences from its failures (potentially resulting in accident situations) will comply with existing safety requirements and regulatory criteria, typically related to the safety of the workers, of the public, and of the environment. Hereby, the focus should not only be nuclear safety and radiation protection, but also conventional safety, which gains a higher importance because the facility will change. When rating the safety of decommissioning activities, administrative and engineered measures (such as specific work instruction, venting systems, shielding) can be considered if they contribute to the prevention or mitigation of adverse consequences from normal (planned) conduct or from failures; such safety measures need to be identified and verified during the safety assessment.

The use of the safety assessment results during implementation of the decommissioning activities is manifold. As the safety assessment sets a frame on what is or isn't possible/acceptable during implementation of the decommissioning activities, safety assessment results can be found in work instructions or in instructions on the maintenance of engineered safety measures. Explanations on how the safety assessment results will be considered during implementation of decommissioning activities were elaborated in the IAEA project, "Use of Safety Assessment in Planning and Implementation of Decommissioning of Facilities Using Radioactive Material (FaSa Project)" [30]. A report on the outcomes of the FaSa Project currently is under preparation, but a brief summary on the outcomes can be found in Ref. [31].

Different approaches can be used to perform a safety assessment for decommissioning. On the international level IAEA published its Safety Standards Series No. WS-G-5.2 [32] on how to perform a safety assessment for decommissioning.[12] WS-G-5.2 was developed in parallel to and inspired by IAEA's International Project on Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material (DeSa Project).[13] The principle of the safety assessment process recommended in WS-G-5.2 is presented in Fig. 2.2.

[12] IAEA Safety Standards Series GSR Part 4, "Safety Assessment for Facilities and Activities" [33] contains general requirements on conducting safety assessments.

[13] The main objectives of the DeSa Project were to collect IAEA Member States' experiences when conducting safety assessments for decommissioning and to extract a common methodology on a safety assessment, including aspects of grading (graded approach) and of regulatory reviews on the safety assessment results. In addition, the DeSa Project provided illustrations on the application of the new safety assessment methodology by means of test cases performed by the project participants on the basis of four real nuclear facilities for which the new methodology was applied. While WS-G-5.2 provides the essence of the safety assessment methodology, the Safety Reports Series No. 77, "Safety Assessment for Decommissioning," on the outcomes of the DeSa Project [34] provides more details including the test case descriptions.

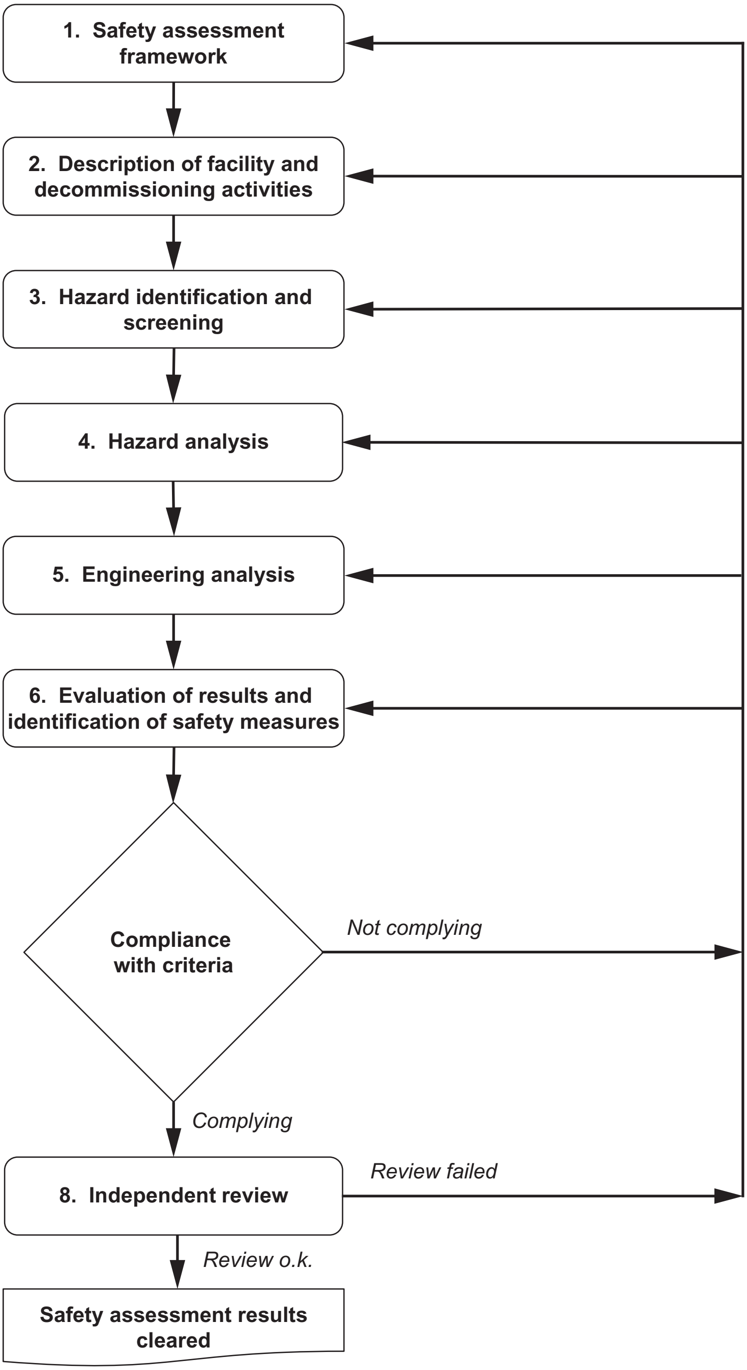

Fig. 2.2 Safety assessment process.
Technical Report Series No. 467, IAEA, Vienna, 2008b; International Atomic Energy Agency, Use of Safety Assessment in Planning and Implementation of Decommissioning of Facilities Using Radioactive Material (FaSa Project)—Scope, Objectives, and Activities (Final Version 1.4), IAEA, Vienna, 2008c; International Atomic Energy Agency, Safety Assessment for the Decommissioning of Facilities Using Radioactive Material, IAEA Safety Standards Series No. WS-G-5.2, IAEA, Vienna, 2008d.

The safety assessment process is an iterative process comprising eight steps that can be summarized as follows:

1. Safety assessment framework
   Within this initial step the frame needs to be defined within which the safety assessment takes place. That is, among others, that the scope of the safety assessment has to be defined (what will be considered, what will not, and why) and that the applicable safety requirements (including nuclear safety and radiation protection requirements) and regulatory criteria (e.g., application requirements, conventional requirements) have to be described. Because it is the main objective of the safety assessment, to demonstrate compliance with these requirements and criteria it is of vital importance to have the full set of applicable safety requirements and regulatory criteria in place and to ensure a common understanding between operator and regulatory body so that the described set is correct and complete.
   In case the safety assessment shall not address all aspects of the facility and the decommissioning activities because results of already existing safety assessments are regarded as still valid and applicable and shall be used, these existing safety assessments need to be summarized and their validity has to be checked. In an example on the decommissioning of a nuclear power plant, it is foreseen to rely on the results of the safety assessment for operation with regard to the temporary storage of spent fuel in the spent fuel pond; in that case the safety assessment for decommissioning has to demonstrate that these results remain valid until the spent fuel will be removed and that no decommissioning activities will jeopardize the safety of the spent fuel (or the opposite: those decommissioning activities that might jeopardize the safety will be prohibited as long as the spent fuel is in the spent fuel pond).
   In the case of a multiple-phase approach (refer to Section 2.3) typically one specific phase is addressed in the safety assessment; for the remaining phases additional safety assessments will be performed for the time being. In such a case the start and end points of the phase need to be described to ensure that the safety assessment is correctly reflecting the phase.
2. Description of facility and decommissioning activities
   Within this second step the facility and the intended decommissioning activities should be described. The description will be based on corresponding descriptions within the final decommissioning plan and is intended mainly as a summary to set the focus on the information needed for conducting the safety assessment. References to existing documentations or to the final decommissioning plan are acceptable (e.g., in the case of a detailed facility description) as long as the referenced documentation is still valid and validity is proven latest within the independent review (step 8).

3. Hazard identification and screening
   In this step, a full scope identification of existing or future hazards (nuclear inventory, radiological inventory, and other hazardous material) should be performed; in addition, external, internal, and human-induced initiating events (e.g., fire, earthquake, failure of safety relevant systems, drop of heavy loads, ignoring of work instructions) that might cause negative consequences to safety need to be identified. Taking into account the normal (planned) decommissioning activities the identified hazards and initiating events become combined with potential failure/accident scenarios; their consequences become screened with respect to the safety requirements and regulatory criteria set in step 1. This screening aims to identify those hazards and scenarios that require further detailed analysis. In addition, all normal (planned) decommissioning activities are also subject to the screening, to ensure that no normal (planned) decommissioning activity itself may compromise safety requirements and regulatory criteria.

The consequence analysis within the screening is typically an estimate using simple calculations and simple tools to quickly arrive at conservative results. Accordingly, purely deterministic calculations or approaches are appropriate for this step. Advanced tools or sophisticated approaches (including probabilistic approaches) might be used within the hazard analysis of step 4 only.

After completion of the screening, a list of hazards and related scenarios exists, which allows a selection of those hazards and scenarios that might compromise the safety requirements and regulatory criteria, as well as that may require further analysis within step 4 if their likelihood is regarded inacceptable. What is regarded inacceptable is either defined within the safety requirements or set be the regulatory body as part of the regulatory criteria (an example on acceptable consequences can be found in ICRP Publication No. 64, Protection from Potential Exposure—A Conceptual Framework [35]).

4. Hazard analysis

For those hazards and scenarios identified in step 3 that might compromise safety requirements and regulatory criteria a detailed analysis has to be performed. Objectives of the analysis are to determine in detail the consequences with respect to the safety requirements and regulatory criteria (e.g., exposure of the workers, exposure of the public) and to preliminarily identify administrative safety measures (e.g., work instructions, emergency procedures) and engineered safety measures (safety relevant structures, systems, and components). For these safety measures the safety functions to be delivered need to be specified precisely; in step 5 these specifications are used as a standard for evaluation when analyzing the safety relevant structure, systems, and components. The specifications for the administrative measures will become incorporated into the related documentation, which typically will be submitted to the regulatory body for approval along with the final decommissioning plan.

The detailed analysis is based on deterministic approaches, but probabilistic approaches can be used also, for example, for effluent or release calculations or for complex facilities for which deterministic approaches might result in results that are too conservative.

Practice shows that scenarios can be grouped, and within a group a representative scenario can be identified, which represents the worst case with respect to their consequences (compromising regulatory requirements and other criteria). Grouping allows limiting the detailed analysis on the representative scenario, but it has to be shown that the representative scenario is the worst one.

5. Engineering analysis

For the engineered safety measures preliminary identified in step 4 a detailed technical analysis is performed. This detailed analysis refers to the technical design and technical properties of existing or new structures, systems, and components and should confirm that the structures, systems, and components deliver the required safety function. The detailed analysis should also confirm compliance of the systems and components with appropriate engineering codes and technical standards.

6. Evaluation of results and identification of safety measures

In this step the outcomes of step 4 and the confirmed outcomes of step 5 are documented in a way that allows concluding on safety: the outcomes should be arranged in a way that they easily refer to the safety requirements and regulatory criteria, the influence of the safety measures on achieving compliance with the safety requirements, and regulatory criteria should be documented.

In addition, all assumptions used as input for the safety assessment should be documented. Furthermore, a sensitivity analysis should be conducted to identify those parameters on which the safety assessment results are sensitive. For such parameters the operator should put in place measures to control the parameters to ensure that the safety assessment results remain valid during decommissioning. If a parameter is too sensitive, modifications of the decommissioning activities should be considered.

7. Compliance with safety requirements and regulatory criteria
   Based on the documentation prepared within step 6 compliance of the safety assessment results with the safety requirements and regulatory criteria should be analyzed and stated. In case of noncompliance with at least one safety requirement or regulatory criteria the safety assessment has failed, and at least parts of the safety assessment need to be repeated.
   Within a repetition input to all safety assessment process steps 1–6 might become changed. Typically and most often, the decommissioning activities become changed to better comply with a safety requirement or a regulatory criteria—this will imply a modification of related parts of the final decommissioning plan and should also initiate a repetition of the risk management for the final decommissioning plan (refer to Section 2.3).

8. Independent review
   In case the safety assessment results comply with the safety requirements and regulatory criteria the safety assessment should become subject to an independent review. This independent review is performed as part of the operator's responsibility to ensure a valid and reliable safety assessment. As such, the independent review is performed on behalf of the operator. According to WS-G-5.2, recommendation 4.49, "The safety assessment is an important contributor to the demonstration of safety during decommissioning and, therefore, the operator's independent review should ensure, that: (a) The input data and assumptions used are valid; (b) The assessment accurately reflects the actual state of the facility and the decommissioning activities; (c) The safety measures derived from the safety assessment are adequate for the decommissioning activities; and (d) The safety assessment is kept updated to reflect the evolution of the facility and the development of knowledge and understanding about it."
   The review should be performed by qualified internal and/or external personnel not directly involved in the development of the safety assessment. The independent review should be documented in line with the operator's quality assurance program.
   If the independent review confirms and clears the safety assessment results, the safety assessment results are ready for further use. If the independent review fails, in other words, the safety assessment results are not internally cleared, the reasons should be documented and the safety assessment needs to be repeated after relevant modifications have been made.

The results of the safety assessment should be at least summarized in the final decommissioning plan, while the full documentation on the safety assessment can be regarded as supporting documentation for the final decommissioning plan. Depending on the national regulatory systems this supporting documentation might be submitted together with the final decommissioning plan to the regulatory body.

Only if the independent review is passed successfully and the safety assessment results are cleared they should be used further; for example, they can be submitted to the regulatory body as part of the approval process. It is important to recognize that conducting a regulatory review of the safety assessment results is within the full responsibility of the regulatory body (Safety Standards Series WS-G-5.2 provides a set of general questions for such a regulatory review). Accordingly, such a regulatory review does not substitute the independent review that is within the full responsibility of the operator—the independent review is a must for the operator.

As explained already, the safety assessment serves, among other reasons, to identify the engineered safety measures (safety relevant structures, systems, and components). Depending on their importance for safety (e.g., relevant for the safety of workers and relevant for the safety of the public) the individual engineered safety measures can be assigned to different safety classes, which relate, among others, to different required availabilities, reliability, technical design standards, and quality standards. Such classes allow optimizing the effort for maintenance, inspection, repair, and replacement. During decommissioning the assignment to a safety class can be changed, but such change (e.g., less availability) must be reflected by an assessment of the impact on safety. Such an assessment can be already done within the safety assessment related to the final decommissioning plan: in that case, the final decommissioning plan will specify the conditions for change and the safety assessment will take this into account. Alternatively (and depending on the regulatory system) a specific safety assessment can be performed, which is limited to the intended change of classification.

As decommissioning proceeds individual engineered safety measures may no longer be needed. This might be due to the elimination of related hazards or due to the transfer of the safety function either to another engineered safety measure (e.g., due to the optimization of residual operation systems) or to administrative safety measures (e.g., the engineered safety measure needs to be dismantled as part of a late phase of decommissioning, where no adequate engineered safety measure is available). In case of elimination of related hazards the removal of the engineered safety measure should have been reflected already in the safety assessment related to the final decommissioning plan. In the case of the replacement the new safety measure needs to deliver the same safety function as the previous one; if not, its use needs to be justified either within the safety assessment related to the final decommissioning plan or by a specific safety assessment.

In Section 2.3 the possibility of arranging the decommissioning of a complex facility in multiple phases was described. With respect to the safety assessment, this approach needs some further explanations:

- In addition to the safety assessment related to the decommissioning activities of the first phase, a safety assessment on the overall decommissioning activities shall be performed (overarching safety assessment). The objective of the overarching safety assessment is to demonstrate on an enveloping conservative level that safety is ensured for the overall decommissioning. The overarching safety assessment follows the process sketched in Fig. 2.2, but the level of detail can be less than that of the safety assessment for the decommissioning activities of an individual phase. The overarching safety assessment will consider the information on the overall decommissioning activities provided in the final decommissioning plan of the first phase.

  Depending on the national regulatory system the overarching safety assessment might be required for different reasons, such as the following:
  - to form a basis for the regulatory body's approval of the overall decommissioning activities, while the results of the safety assessments for the decommissioning activities of a specific phase are used to confirm that their impact on safety is already covered by the overarching safety assessment; and
  - to provide input for the stakeholder involvement process.
- For each phase a safety assessment needs to be performed to demonstrate safety for the decommissioning activities related to the specific phase described in the final decommis-

sioning plan of the phase. This safety assessment follows the process as sketched in Fig. 2.2. As part of the safety assessment the interfaces between phases need careful analysis to avoid unacceptable interferences. In addition, as part of step 7 of the safety assessment process the safety assessment results for a phase need to be compared also with those from the overarching safety assessment. In case of results exceeding those for the overarching safety assessment the reasons need to be investigated because the conservatism of the overarching safety assessment is no longer given. The final decommissioning plan for the phase should be modified and the safety assessment (and risk management process) should be repeated to solve the excess. If the excess cannot be solved, a consultation with the regulatory body is advisable because depending on the national regulatory system severe consequences may result. Independent from such a consultation, the overarching safety assessment should cover all safety impacts of the individual phases and might become modified on the basis of a modified description of the overall decommissioning activities.

Details on the overarching safety assessment, on its relation with the safety assessments for the individual phases, and on the evolution of the safety assessment for later phases were elaborated within the previously mentioned IAEA project, “Use of Safety Assessment in Planning and Implementation of Decommissioning of Facilities Using Radioactive Material (FaSa Project)” [30] and will be explained in a report currently under preparation.

2.5 Future trends

Today, safety and radiation protection are ensured during the decommissioning of facilities. This is, among other reasons, due to clear regulations guiding the planning and conducting of decommissioning activities, due to appropriate technologies, and due to qualified personnel and experience feedback affecting all areas involved in decommissioning. Nevertheless, decommissioning will continue to improve, but recently, no noteworthy trends are foreseen except for the following:

- The multiple-phase approach is an established concept for the decommissioning of a facility. As mentioned in Section 2.3 the number of phases needs to be balanced. E.g., while in the past four phases was typical in some recent German decommissioning projects on nuclear power plants, a trend can be seen to limit the number of phases to two. Whether this trend will continue to only involve one phase may depend on the type of facility, and it may especially depend on whether the operator can rely on sufficient experiences related to the decommissioning of the facility type.
- Perhaps inspired by the removal of intact large components with ex situ or off-site dismantling and decontamination, some decommissioning projects intend to apply the ex situ cutting and contamination (without deferral period) for more types of components than for just large components. The concept behind this intention is a systematic split of the decommissioning process into a dismantling part, in which a component is disconnected and removed from its in situ location, and a waste management part, in which a component is cut and decontaminated/processed ex situ or in an external facility. Accordingly, such a split decouples the dismantling process and the waste management process allowing both (to some extent) to execute mostly independently and thus may be beneficial to the overall schedule of decommissioning.

- Project risk management is already now part of a good project management approach. However, up to now experience exchange on decommissioning specific risks (i.e., threats or opportunities for a decommissioning project) and project risk management specific to decommissioning is not well established and international guidance is not available. The first initiatives taken by IAEA's DRiMa Project have been briefly reported on in Section 2.3. The importance of project risk management for a smooth decommissioning project process and for cost savings becomes more and more obvious to decision makers and managers of decommissioning projects and was reflected in 2016 by the International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes [36]; the conference suggested the development of guidance on the management of project risks in decommissioning and remediation programs. It can be expected that IAEA will make a related initiative within the next years.

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The cultural aspects of decommissioning

3

M. Laraia
Independent consultant, Rome, Italy

3.1 Introduction

A few years ago it became evident that not everything in decommissioning can be reduced to technologies or procedures, although all of these remain of overwhelming importance. There is a somehow "hidden" "soft" side, which has to do with motivation, behaviors, and mindsets, in other words, "culture." It goes without saying that "cultural" aspects are more difficult to single out, measure, evaluate, and amend, if needed, than other aspects of decommissioning. Various approaches to cultural metrics have been adopted, but a feeling remains that the essence of the problem may still be missing. And the multidisciplinary nature of decommissioning requires a holistic approach, which can be further elusive [1].

Edgar H. Schein, commonly deemed the founder of organizational culture as a standalone science, defines organizational culture as follows: "A pattern of basic assumptions invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration that has worked well enough to be considered valid and, therefore is to be taught to new members as the correct way to perceive, think, and feel in relation to those problems" [2].

Several factors that determine the cultural aspects of decommissioning are already evident from this definition:

- Culture shapes the identity(ies) (e.g., of the team performing decommissioning);
- Culture creates a sense of "belonging";
- There are many possible sets of conditions, humans can adapt to different conditions, and different cultures are created accordingly;
- No culture is intrinsically superior to another;
- Cultures are organized, and the parts fit together;
- Culture produces the distinction of and the (inevitable) interactions between "us" and "the others."

In other words, every person wants to belong to a group of people, to be accepted by the other members of the group as "one of them," and to be recognized by outsiders as a member of that group. The members of the group share backgrounds, circumstances, tastes, and values (with some individual variations). And the group speaks a common "language."

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The following provides a brief outline, which exemplifies the expected cultural issues in nuclear decommissioning:

Teamwork

Teamwork is essential in decommissioning in that (a) the working environment changes at all times, (b) different organizations work together—typically operations staff and contractors, and (c) different types of expertise are required at the same time (e.g., waste management and dismantling techniques).

Trust

The new teams, often short lived or even ad hoc, cannot always rely on past experience and familiarity with each other's competences, work modes, and views. Establishing these teams in a fruitful way, training them, and building trust between team members are all essential for safe, timely, and cost-effective performance.

Shared situation awareness

Shared situation awareness is important for making the right decisions and for ensuring implementation of these decisions after they are made. Another important part of situation awareness is the identification of risks pertaining to a decision or work task.

Goal conflicts

The new targets, often with strong requirements on economy, efficiency, quality, documentation, and flexibility, require people to balance goals; for example, safety goals versus efficiency goals, workers' goals against other stakeholders' goals, etc. It has been reported both in the nuclear and other industries that errors, incidents, and other mishaps are more likely to occur when people or organizations experience goal conflicts.

Confidence to speak up

A "guts to speak" or "no-blame" culture can be essential, especially in flexible organizations, for combining efficiency with safety. A lack of such confidence has in several projects imposed undue risks, as well as significantly reduced motivation.

Change management

Some elements of change management will need to be taken into account. Special focus should be placed on individual motivation and acceptance when change is inevitable.

Decommissioning is basically demolition and waste generation. This simplification may lead to a perception of low priority and lack of interest, more likely in a highly qualified team (researchers, etc.) who have necessarily to adapt to changing work conditions.

Decommissioning is often a "one-end" process. Appreciating one's position as "working oneself out of a job" is hardly conducive to good motivation and performance. Adjusting oneself to changes of this kind can be hard.

Stakeholders

There are many stakeholders in nuclear decommissioning, ranging from those internal to the decommissioning organization (from top management to regular staff), to contractors, and to the general public. These different groups—and their subgroups share different identities and cultures. Success of the decommissioning project imposes at least some harmonization (see Chapter 6).

3.2 Cultural review as the latest development in the history of nuclear decommissioning

The dawn of the third millennium brought about a growing awareness that technology alone was insufficient to lead a large decommissioning project to safe, timely, and cost-effective completion. Until then, the focus had been largely placed on technologies and a large amount of R&D efforts (from the US Department of Energy, European Commission, IAEA, and Japan) was invested to improve them: it is well recognized today that decommissioning is a mature industry, not unlike the car industry. And yet, like the car industry, decommissioning techniques are being constantly improved and optimized. This implies an ever-changing assessment of safety: what was safe 20 years ago is not safe enough today. Standards have been raised.

In the first decade of the 2000s, more attention was given to the experience available globally regarding the management and organizational aspects of decommissioning. This knowledge began to be collected in IAEA technical reports [3]. The current feeling is that, while decommissioning technology is generally well understood and capable to tackle almost all decommissioning projects, organizational aspects are more difficult to “appreciate.” First and foremost, organizational aspects are difficult to see, measure, assess, and correct than the technological sides of decommissioning.

Gathering and sharing lessons learned, and promulgating guidance, on technological and organizational facets of decommissioning remain essential, and the decommissioning programs of major national and international organizations remain focused on those aspects. But more recently, a new paradigm came to light. Decommissioning is especially sensitive to the impacts of “cultural” inadequacies. In this regard it is different from other fully “procedurized” and well-regulated phases of a facility’s service life such as operations. This difference is due to the dynamic nature and the necessary flexibility of the decommissioning process, which inevitably leaves a large amount of room for unknowns, unexpected occurrences, and the need for action in circumstances that cannot be predefined in detail. Decommissioning is intrinsically multidisciplinary (including radiological and industrial safety; radioactive and hazardous waste management; civil, mechanical, chemical, and electronic engineering; costing and funding; stakeholder involvement; etc.), and this dictates that the abovementioned disciplines be managed within an integrated vision, which is indeed another cultural point of distinction.

3.3 The cultural changes between operations and decommissioning

Regardless of the opportunities offered by organizational changes, it should be recognized that the transition from operations to decommissioning reflects in a number of potentially hard-to-digest cultural changes.

An operations organization is generally permanent and stable. Changes are rarely radical, and the “skeleton” of the organization will in essence be permanent or long lasting (including job security). This is no longer the case when the organization starts transitioning to decommissioning, and the original organization or its remaining parts undergo significant, continual changes in a relatively short time. Many of these changes involve change from stability and routine into temporary and task-based roles and activities. Regulators will assume different objectives; inspections will be more frequent; many new stakeholders (the media, local communities, the corporate headquarters, etc.) will appear more frequently on the scene and start asking unexpected questions (Section 3.4 of this chapter). Working teams will change with an increasing attendance of newcomers (the contractors) and the gradual disappearance of old teammates. The contractors will introduce new cultures (including differences in backgrounds, working habits, quality assurance programs, and even languages—or at least jargons and slangs). The old staff will have to learn and be trained for new jobs that would be more in line with the specific competence of the contractors: this can be viewed by someone as a loss of hard-earned prestige. Older staff can be reluctant to accept a drastic change to their lifestyles.

It should be noted that cross-cultural interactions are exacerbated by the presence of multiple contractors working on the plant at the same time. In such a case harmonization will be needed not only between the responsible organization and the contractors, but also between different groups of contractors. In certain decommissioning projects the responsible organizations have opted to rely on one prime contractor, rather than many smaller-size contractors. Typically it is up to the prime contractor to choose between doing all work alone or to trust single subcontractors to complete some parts of it.

Once the operations-to-decommissioning transition is over, a new cultural balance is established between all parties. It is possible and desirable that initially different cultures have reconciled, perhaps having reached a “middle ground” of mutual understanding. The most critical part is the transition period when the old balances are disappearing and the new balances are not fully in place. Change in progress at Phenix Nuclear Power Plant (NPP), France is assessed in more detail in Ref. [4]. General guidance to change management is given in Ref. [5], one out of many publications on the topic.

3.3.1 The motivational aspects of decommissioning

After final shutdown, drastic changes will inevitably occur in jobs and the use of individual expertise, which may have an impact on individual or collective motivation. With new job requirements emerging, a number of respected competences may turn out to be irrelevant: a neutron specialist may be offered a job in demolition, with no regard being given to his former profession. Besides, some staff may view the plant shutdown as premature, politically driven, and a sheer waste of money and resources. This view may easily cause a rift between, on one side, the plant staff and, on the other side, the corporate management and the government. These perceptions and more of this type can make the staff reluctant to fully engage during decommissioning.

Uncertainty about the timing, schedule, and end state of the decommissioning project can exacerbate motivational issues. For example, in one scenario, the decommissioning program is firmly established but limited in time, in other words, the plans exist for a finite time but are subject to review of priorities, and budgets may significantly change. This strategy is sometimes called "incremental decommissioning" or (more brutally) "stop and go." It entails some measure of certainty, but changes can be significant and ultimately impact motivation. An even worse scenario appears when the program is uncertain and plans change with every emerging issue or political decision. This strategy is discouraged by international guidance because it will impact, among other aspects, the workforce occupations, training, and working hours.

The timescale of the program may also change, in other words, it may accelerate or become delayed. Provided the plans are clear, the negative impact on motivation can be reduced. Difficulties can arise where management have based reward or career/retirement promises on the previous program, for example, a retirement timetable based on a set timing or career moves based on completion of a project and availability of redeployment opportunities.

In this domain the reader may usefully consult Energy Institute [6].

For the individuals who have been working at an operating facility and expect to be engaged in the facility's decommissioning, a number of uncertainties will exist:

- How long will I have a job? Will early retirement be an option (depending on age and national legislation)? If I am made redundant will I be offered compensation? Conversely will I be offered a bonus for staying with the decommissioning organization?
- Will I be forced to work for a contractor?
- What will be my new job? What will the salary be? What will be the short- or long-term prospects for my professional development?
- Will I have to relocate to take a new job? What will my family do? Will I be able to commute from home to the workplace?
- Will I be offered training to start a new job "properly"? What will the workload be? Will I have to familiarize with new coworkers? Will I like them?

The negative view of these uncertainties could lead to loss of motivation and often to the "working-yourself-out-of-a-job" syndrome. Thus, the decommissioning project may become the sad end of a professional career.

An unmotivated workforce could have a negative impact on the business through [7]:

- Lower productivity (or worse, boycott, sabotage, or vandalism);
- Frequent incidents;
- Higher rates of absenteeism and strikes;
- Personal conflicts;
- Less readiness to train or change to new jobs; and
- Greater need of supervision.

It is a fact (although rarely publicized) that certain decommissioning projects have been delayed by the lack of cooperation by workers who did not feel motivated to do the work quickly and well. In other words, a form of "passive resistance" may appear, which can be hard to promptly identify and correct.

A more frequent reaction to a negative understanding of this situation would be workers leaving the organization on their own will. People might leave even if the proposed change is a good change because they find it difficult to cope with.

These issues can be solved through individual management schemes and the identification of resources offered by national welfare and market opportunities. Typical mechanisms to enhance motivation may include the following [7]:

- Retaining staff by helping them develop new skills (e.g., by training)
- Pension schemes
- Promotion, empowerment
- Financial benefits (e.g., linked to performance)
- Nonfinancial benefits (e.g., holidays, health insurance, school fees, good working atmosphere, etc.)
- Providing work-life balance (e.g., relocation assistance, family leave, counseling, etc.)

Timely planning for postdecommissioning redevelopment of the nuclear site can be a strategic move to solve social issues, maintain personnel motivation, and assist in the smooth progress of decommissioning. Decommissioning workers can feel more motivated if they know that there is a future for them when decommissioning is over: their qualifications and skills will be reused locally with no need for moving hundreds of km away (job mobility is not at all socially acceptable in many countries).

General guidance to teamwork is given in Ref. [8]. Motivation in workplaces is dealt with extensively in Ref. [9]. These are only two publications amongst dozens in this general field. Fig. 3.1 shows a team dismantling a research reactor.

Fig. 3.1 Dismantling of a research reactor.
M. Laraia’s photo, 1987.

3.3.2 Implicit versus explicit coordination

The distinction between implicit and explicit coordination (a form of, respectively, implicit and explicit knowledge) can be useful in understanding the nature of the needed coordination. This aspect is especially critical in decommissioning due to the work teams changing from former operations. Explicit coordination implies that team members communicate to express their plans, actions, and responsibilities or purposely coordinate by the use of schedules, plans, and procedures. Implicit coordination is about the team's ability to act in concert without the need for overt communication. Implicit coordination is founded on the knowledge that the team members share about the task and about each other; in other words, they share a culture. This form of coordination is typical of long-standing teams who have become used to humoring individual personalities; in fact most of them are personal friends. Most teams will apply a mixture of implicit and explicit coordination, and the pros and cons of implicit and explicit coordination depend on the nature of the task, the task environment, as well as the "chemistry" of the team. The advantage of implicit coordination during high workload situations has been ascertained. But implicit coordination does not necessarily produce adequate performance. In novel tasks—there are many during decommissioning—it might be necessary for efficient performance to be explicit in defining the problem, defining strategies, and having contingency plans. The "costs" and penalties of implicit and explicit coordination have different features. For example, training time and efforts are needed to form the mutual basis of understanding for implicit coordination, while explicit coordination has a higher communication "cost" during execution than implicit coordination [10] (Fig. 3.2).

Fig. 3.2 Implicit or explicit coordination? The former was generally the rule in earlier times. Photo by M. Laraia, 1983.

3.3.3 Building trust

Trust is a key factor in teamwork and a frequently raised issue in decommissioning. Do we trust the new management? Do they have our best interest in mind? Do I trust this new colleague who never worked with us before? Do we trust that the people who wrote this procedure for a task we have never done had the right competence to do so? Trust is often easier to build in an environment of stability and routine, where an individual's exposure to other individuals actions and decisions is modest and well known. In a changing situation where jobs and tasks are no longer fixed—where, for example, the nature of safety risks changes and today's key qualifications may be obsolete tomorrow—vulnerability increases. Trust is also essential for motivation.

Trust needs to be just adequate. While too little trust in teammates, subordinates, or leaders may lead to, say, excessive verification of information or questioning of arguments, too much trust may lead to complacency and even relaxation of performance standards.

Trust is also one of the coordination mechanisms for teamwork as described in Section 3.3.2. When building the new organizations and teams for a decommissioning project, the teams, often short lived or even ad hoc, cannot always rely on past experience and familiarity with each other's competences, work modes, and views. Establishing the new teams in a fruitful way, training them, and building (the right measure of) trust between team members is essential for safe, timely, and cost-effective performance in a decommissioning team.

For communication across boundaries to work, people need to trust each other. In times of change, trust must be constantly worked upon, or it may easily break. Several decommissioning projects have been struggling with trust.

3.3.4 Conflicting goals

Several types of goal conflicts can been identified in the literature [11]. A typical case in question for decommissioning is the organizational goal of maximizing productivity (e.g., tons of waste generated per month) while the goal of those responsible for safety is to take all the time needed to assess, and make accurate plans for, the minimization of hazards. In practice productivity can cause safety concerns for reasons such as the following:

- New hires not mentored (reportedly, mentoring takes >10% time).
- No monitoring of workload, fatigue, and stress.
- Old equipment kept in poor condition ("It is to be demolished; why bother maintaining it? It's unfortunate that the equipment still must serve its purposes for a while").
- Lack of human factor risk assessment under new circumstances (e.g., skills shortage).

One type of conflict arises when an externally imposed goal conflicts with the individual's personal goals. For instance, it appears that when subjects were assigned (e.g., in decommissioning) a goal that was significantly higher than their previously chosen personal goal level (e.g., in former plant operation), the commitment to the assigned goal and task performance was lower than when personal goals were set after the goal was assigned.

When an optimal solution cannot be found whereby all goals are met, an acceptable strategy is generally employed resulting in a solution that's "good enough" from the standpoint of the person performing the activity. Such satisfactory strategies are essential for the overall performance because they allow individuals and organizations to operate under time and resource constraints.

A case reported to the writer is quoted here as an example. During operations, keeping the environment clean from contamination is essential. During activities of cutting and grinding, which continue for days or weeks, this goal is no longer a viable approach, and within certain work areas staff should rather focus on keeping contamination within acceptable levels and not spreading it to other, cleaner areas. Still, their inbred safety focus will often lead them to clean up meticulously every day, unnecessarily losing valuable time.

In order to model goal conflicts [11], several relevant factors should be identified:

- Goal commitment: The more conflict individuals experience among different goals, the less committed they are to one goal;
- Goal attainment: Beliefs about whether the task can be carried out successfully;
- Self-efficacy: Beliefs about one's personal ability to achieve a task;
- Need for achievement: A personality trait describing a person's ambition to accomplish difficult tasks; and
- Outcome emotions: Performance has emotional consequences that will affect future performance.

3.3.5 New procedures

There is a continual need during decommissioning to draft procedures for tasks that have never been performed before. Due to lack of familiarity with decommissioning by the drafters, the procedures may be imprecise or lack the necessary degree of detail. Conversely, procedures may be written with too high a level of detail and be overprotective because the drafters want to be on the safe side, or they may be obsessed with procedural compliance. Too stringent procedures may lack the flexibility needed to cope with unexpected events or with an incomplete knowledge of the working environment. It is reported across organizations that workers have a hard time choosing between "straight forward and efficient methods" and following the procedure exactly. The right balance between procedure and competence (taking due account of training imparted) should be ensured. This is often a problem of coordination: enforcing procedures is easier when the objectives of the procedure are known and communications with the procedure drafters are open. Overall, those expected to implement procedures taking part in drafting them is advantageous. Sometime a hotline for technical support can help. Also, there can be an issue of trust (Section 3.3.3): those drafting the procedures may belong to a different organization than those implementing the procedures. An additional point is related to the deep aspects of culture, namely ingrained traditions and customs (Section 3.3.7): in some nations, rules, directives, and procedures are taken as suggestions (but "I know better"), while in other nations they are little less than God's commandments. Decommissioning procedures should be regularly reviewed under a continuous improvement program based on feedback by the implementers.

3.3.6 Safety culture

Safety culture is commonly intended as a subset of organizational culture. Safety culture focuses on the intents and attitudes that affect safety performance.

Broadly speaking, safety culture can be defined as a pervasive (i.e., through all management and operating tiers of a given organization) expectation that workers will adopt safety as the prime concern of their activities, that supervisors will embed safety considerations in their decision making, that management will include significant safety margins and contingencies in their vision and goals, and that the whole responsible organization will promote safe behaviors and punish omissions and inattention that compromise safety. A good safety culture should be alert in locating existing or potential hazards, proactive in establishing mitigation measures, and attentive to lessons learned—whether good or bad (including near misses).

Similar to organizational culture, there is an intangible element to safety culture. While some of its elements can be measured and regulated (e.g., qualifications of the workers, number of training courses attended, number of inspections, etc.), safety culture as a whole is hardly quantifiable.

Regulators grant (decommissioning) licenses based on compliance with regulatory requirements. However, they have no power or means to enforce "cultural" requirements. Investigations often identify poor safety culture as a root cause (bad attitudes led to bad consequences). Therefore, the justification for a safety culture program is the avoidance of extra training or repair costs later (prevention is better than cure). This is not a regulatory requirement. It is more of a warning. But safety culture remains broader a domain than regulations (likewise, driving safely goes beyond respecting traffic rules).

Management of safety is important throughout both operations and decommissioning. Typically during operations similar hazards are dealt with on a daily basis. The main hazards of operations are radiological. The decommissioning phase is critical because it leads operators to dismantle the existing equipment, which calls for the workers to be close to radioactive sources and take industrial (i.e., nonradiological) risks. This in turn requires the adoption of work practices different from operations and use of new tools, like remotely-operated equipment or robots.

A challenge in decommissioning could be a wrong understanding—especially among former operations staff—that decommissioning is a trivial activity, which can be tackled if and when needed. This "cultural" attitude can induce a sense of sloppiness and complacency, which is inimical to safety.

In decommissioning, the industrial risk is greatly increased. This also means that the safety focus may vary: one task may pose high chemical risk, while another may pose a high risk of radiological exposure. This is another cultural issue: the former operations staff have a radiological background, which needs to be adapted to new hazards. Training is mandatory in this regard. Vice versa, many contractors are familiar with nonradiological hazards but may feel out of place in a radiological environment. In many countries, nuclear regulators belong to a different organization than industrial regulators.

The plant staff will have to work closely with the contractors, often in joint teams. The former staff and the contractors will typically have different professional backgrounds, different priorities, and different prospects: in other words a different "culture." To ensure that safety is maintained at all times, harmonization and constant supervision by the top management will be imperative. In this regard it is important to stress that decommissioning tasks can be delegated to contractors, but the overall legal responsibility stays with the licensee (usually the former operating organization). Moreover, there can be increased risk levels due to concurrent activities; the undertaking of one decommissioning task may influence risks for another. Tasks are much less repetitive in decommissioning than in operation, and many challenges can be one-of-a-kind. Even when a task is similar to one that has been performed before, unknowns are possible.

During plant operations procedures are developed and perfected over time to become workable, and operators are trained to follow these routinely, including among others, safety provisions. By contrast, in decommissioning the new tasks require new and unfamiliar procedures and new safety provisions (Section 3.3.5). Occasionally radiological requirements may conflict with industrial safety requirements (e.g., taking smear samples for radiological clearance purposes from a 20-m high ceiling).

And finally, a sound safety culture requires a learning organization. Without it the organization is doomed to repeat mistakes and ignore successes. Operational experience feedback is therefore critical. However, this can be difficult to achieve, especially if there are reservations over disclosing (perceivedly embarassing) information or a risk of litigation.

3.3.7 The cultural "heritage": Traditions, customs, and mentalities

This section briefly presents the most elusive, least tangible part of a culture, which is located inside a person's mind. This refers to national, local, and ultimately personal identity (as affected by the environment in which we were born and have grown up). According to [12] identity is defined as "the reflective self-conception or self-image that we each derive from our family, gender, cultural, ethnic, and individual socialization process." According to Hall [13], three levels of identity can be established:

- "Personal (what makes us unique)
- Relational (our relationships with others)
- Cultural, communal, or social (large-scale communities such as nationality, ethnicity, gender, religious, or political affiliation)."

In intercultural communication, participants will have to search for a middle ground between their different approaches (to communication, working behaviors, etc.). While this approach was mostly studied for peoples or distinct population groups (e.g., immigrants in a host country; see Ref. [14]) the implications to different groups of people interacting in a decommissioning project should not be neglected. It should be noted that, although mighty, cultural predominance often works inadvertently. The growing globalization of industries and businesses worldwide will make intercultural interactions in workplaces more and more frequent.

Like in ethnic interactions, certain phenomena may appear even in smaller team interactions, such as what's stated in Ref. [13]:

- "Stereotype—categorization that mentally organizes your experience with, and guides your behavior toward, a particular group of people.
- Prejudices—deeply held negative feelings associated with a particular group (anger, fear, aversion, anxiety)."

To ensure a successful blending of cultures it is important to do the following:

- Assess cultural adaptability of both organizations joining the common project.
- Foster common values rather than giving priority to the values of one organization.

Complications can be due to a number of factors, Ref. [15]:

Culture has multiple tiers: What you see on the surface may hide deeper differences. People are not all the same, even in a given cultural group. So, beware of cultural categorizations. However, individual variations do not stretch too far from the average (typical) group's pattern.
Culture is ever-changing: *C*ultural groups adjust to changed circumstances. This is often called socialization. In fact, this is the advisable outcome of the creation of new teams and new interactions (e.g., during decommissioning).

Leadership is a notion that plays a great role in establishing relations (for our purposes, in a decommissioning project). It has strong cultural connotations (i.e., the ways leadership is exerted is profoundly affected by cultural values). It can be pictured as a mechanism to solicit action from people by providing objectives, guidance, and interest.

- Objective—Gives workers a reason to take action.
- Guidance—Gives them instructions/framework/boundary conditions, etc. to take action.
- Interest—Gives them the will to take action.

Leaders must properly interact with their subordinates (people expected to take action as indicated by the leaders). However, depending on nonbusiness circumstances (the broadly cultural sides), interactions in business may vary considerably and, as a consequence, be more or less successful. It should be noted that interactions highlight a two-way process: success depends on the compatibility of cultures of both (or multiple) parties. It can be typical of decommissioning that leaders are from a different organization than their subordinates, even from a different country. A generic assessment of the cultural role of contractors vs. staff in decommissioning projects is given in Ref. [16] and other publications.

A typical case is the technical cooperation (for our purposes, in decommissioning projects) offered by the IAEA to developing countries upon their request: IAEA experts may find themselves acting as leaders in a project for which others are responsible but less competent. It is therefore important that IAEA experts do not act as the "bearers of a new truth" because this may cause resentment among their listeners, usually people from different culture. But for all intents and purposes the IAEA is an important stakeholder in technical cooperation projects. Intercultural communications are essential to the success of the project (Fig. 3.2). All levels will be involved either on the IAEA side (top management, Technical Cooperation Department management, and officers responsible for the administrative management of the project, staff, or external experts seconded by technical departments of the IAEA) or on the recipient country's side (government, research center management, and local experts). The internal, multicultural nature of the IAEA is in itself a challenge to reaching a coherent approach when running projects with outsiders (Fig. 3.3).

Table 3.1 exemplifies typical aspects of two—quite different—cultural models. It is easy to derive the implications on mutual interactions when a member of the "authoritarian" model (e.g., the decommissioning team leader) interacts with members of the "collaborative" model (e.g., his or her team).

Fig. 3.3 The Vienna International Centre, Austria, where IAEA Headquarters are located (Woodhead, Managing Nuclear Projects, 2013).

Table 3.1 **A typical example of two cultural models**

"Collaborative" model	"Authoritarian" model
• A trend towards "flat" structures	• Traditional hierarchical organizations
• Accessible, "democratic" management	• Patriarchal management
• Uninterested attitude to privileges and hierarchies	• Visible wealth, power, and authority
• The leader tries to be one of the group or the first among peers	• The leader decides and that's it
• Streamlining, "soft" society	• Competitive society
• "No-blame" culture	• Who is the culprit?
• Reputation of the group and participation in common success	• Individual success

Table 3.2 A typical example of two cultural models

"Individualistic" model	"Collectivistic" model
The fittest survive	Pity the losers
The interest of the group is the summation of individual interests	The group is an inseparable entity
Sharp distinction between in-groups and out-groups	Limited distinction between in-groups and out-groups
Internal communications are direct and no-frills	Internal communications are dictated by customs and constraints, and are often indirect and implicit
Self-esteem is based on independence and uniqueness	Self-esteem is based on group's acceptance

Table 3.2 illustrates two more cultural models elaborated from a concept initially developed by [17]. Once again, interactions between members of two groups can be—to say the least—problematic.

A consequence of a manager unsympathetic to team members (because he has a different culture) is that s(he) will tend to ignore the facts-of-life. For example, s(he) can do the following:

- Assume unrealistically low error rates.
- Have no error correction plan.
- Never go to the plant (s(he) does not want to "get her/his hands dirty").
- Discriminate team members in two classes (the smart and the others).
- Hire and fire quickly.
- Be secretive.
- Treat the team as a hazard rather than an asset.
- Not listen: it is rare that the cause of an incident has not previously been made known to management.
- Disregard the time needed for communication in task plans (i.e., in shift handover).
- Assume that everything is "operator error."
- Run "perfunctory" risk assessments.
- Direct blame-based investigations (note: a no-blame culture is a prerequisite for transparency, completeness of information, and fixing of mistakes).
- Include no human factors in risk assessments.
- Stop questions or requests before identifying the root cause of an incident.

General guidance on cultural interactions in and between teams, and between teams and others (e.g., leaders, managers), is given in Refs. [18] and [19].

3.3.8 The language barrier

Jargon can be defined as the specialized technical terminology characteristic of a specific subject and of a specific group (e.g., in decommissioning, the reactor staff who were at work together for 20 years).

To use jargon to communicate, you must know the people you speak to. All industries use jargon (decommissioning is no exception), and this is acceptable, because most practitioners of a given sector have a basic understanding of the contents and related jargon. But problems will arise when different groups collide (e.g., in decommissioning, the operations staff and contractors from another country). While jargon can be useful when communicating within a given group (e.g., it increases the sense of "belonging" and in-group solidarity), insistent or undefined jargon can lead to confusing messages and ultimately to the risk of misunderstanding between different groups.

In teamwork the objective is clarity. Unless there is a strong reason to use jargon, it is best not to use it. If jargon is used, make it understandable.

The following is a shortened list of terms used among US construction workers, which can be representative of the language used at some decommissioning sites. The reader will note how certain terms are hard to understand for the noninitiated and can cause potentially dangerous misunderstandings.

> "Balls: In land surveying, it refers to a measurement ending in a double zero. For example, a measurement of 7.00 is referred to as '7 balls'.
> Cowboy: A scraper operator.
> Ginnie hopper: An apprentice grade-checker or surveyor.
> Juice a brick: To recharge a battery or other rechargeable.
> Modify: To alter by accident, e.g., 'Boss, I just modified your fender with my dozer'.
> New York screwdriver: A very large hammer.
> Plumber: A serious insult to a pipefitter.
> Steel monkey: Used to refer to staff working at heights.
> Tin knocker: A sheet metal worker.
> Two-block: A crane operator who has sloppily hoisted the crane's ball and hook into its boom." [20]

Slang is defined as a language occurring mainly in casual speech, including typically short lived verbal inventions that are intentionally used instead of standard language for showing-off. Slang is the language of the moment within groups that formed in close association. But using slang to convey information can be tricky. First, slang is short lived. Slang words or phrases may soon become unclear, especially to others who are not used to it.

And lastly, idioms are groups of "fossilized" words having a meaning independent from those of the individual words. English literature has many uses of idioms: Shakespeare developed many idioms currently still in full use; some examples are "a rose by any other name would smell as sweet," "a fool's paradise," or "wearing your heart on your sleeve." But like jargon and slang, idioms should be used cautiously in communicating with people you are not sure will understand.

3.4 Cultural interactions with stakeholders

The term "stakeholder" might be defined in many ways. A stakeholder is an interested or concerned party (in decommissioning, for our purposes). Stakeholders can be broadly split into two categories [21]:

- Statutory parties
- Nonstatutory parties

Statutory parties include the government departments, the nuclear and environmental regulators, elected officials, legal representatives, etc. Nonstatutory parties include employees, trade unions, contractors, the local community, nongovernment organizations (NGOs), historical and archeological societies, and basically any party claiming a right to discuss the decommissioning process and its impacts. Because this section is about cultural interactions, it will mainly address nonstatutory parties, especially the public communities, that own generally a different "culture" from plant operators and regulators. Therefore the notion of (cross-) cultural interactions will apply to its full extent (Fig. 3.4). However, the different roles and interests pertaining to the operating organization (corporate management, plant management, employees, etc.) should not be disregarded in these cultural interactions: it is to be assumed that different operator's categories own different cultures.

Because there are multiple stakeholders in a decommissioning project, their knowledge (i.e., cultural) interests vary, ranging from the full coverage of technical and organizational aspects to key parameters summarizing, for the uninitiated's sake, the achievements and impacts of a project. The latter data is often referred to as performance indicators [22]. In turn, indicators will differ from one stakeholder to another: financial institutions will be interested in how effectively the money is being spent, while the environmentalists will want to know about radioactive discharges or progress of site cleanup.

An integrated approach to knowledge means that connections can be made between the various entities, thereby creating a framework where knowledge can be shared and transferred to and between stakeholders. The organizational strategy should reflect

Fig. 3.4 Construction of a biodiesel plant at Greifswald nuclear power plant, Germany. A large decommissioning project has been underway at Greifswald since the early 1990s. To mitigate the social impacts from decommissioning, a massive industrial redevelopment was launched and is still ongoing. This has requested coordination of statutory parties with citizens' committees, trade unions, and industrial entrepreneurs.
(Nuclear decommissioning—planning, execution and international experience, in: M. Laraia, Woodhead Publishing, 2012, ISBN: 978-0-85709-115-4; Fig. 18.10).

the multidimensional nature of knowledge (i.e., the culture) and not restrict itself to managing individual information sources upon request.

As mentioned earlier, the beginning of a decommissioning project will see the participation of many new stakeholders. This has to do with decommissioning being viewed as a major change in a facility's lifecycle. Whereas plant operations are perceived as routine and static, decommissioning is viewed as dynamic, multiform, and somehow unpredictable. These features will attract the interest of the media and the worries of the local communities.

Typically the main reservations and concerns raised by nearby communities include, but are not limited to the following:

- The perceived disruption of traditional lifestyles, for example, farming or small businesses.
- Safety—the residents may feel threatened by decommissioning. The plant is often viewed as a "black box" spreading evil once broken open.
- Uncertainties about postdecommissioning scenarios (land planning, industries leaving, schools and catering services being discontinued, etc.)
- Concerns about devaluation of privately-owned properties.
- Increased vehicle traffic, including the shipment of radioactive and other hazardous waste.

The general public is typically identified as the "man-on-the-street." This means that these people possess little or no understanding of nuclear sciences and the range of their broadly technical knowledge is variable, but more often verging on little more than basic education. There is, therefore, a culture gap, which should hopefully be minimized in the cross-culture debate.

Planning and implementation of decommissioning can be lengthy and multifaceted, so it is vital that all stakeholders are regularly kept "in-the-loop." This requirement can be fulfilled through circulation of newsletters, media releases, general or topical stakeholder meetings, and events such as the following [21]:

- Customized meetings to address specific concerns.
- Expert presentations.
- Site tours and demonstrations.

It is also essential that the project website maintains an up-to-date description of the whole mission, so orienting consultation needs and easing the understanding of progress.

While it is impossible to mitigate all stakeholders' concerns, it is up to the responsible organization(s) to be ready and willing to listen to, and understand, the values and customs that inform their views (in other words, their "culture"). You may disagree with their views, but this does not necessarily preempt them. Not everyone likes change, and when that change is clearly impacting lives, it is taken very seriously.

Although human priorities and expectations have similarities worldwide, it should be appreciated that each country (and often each site) has a unique culture (i.e., education, customs, and language). Therefore, a tailored approach is highly desirable. The following steps are needed from an operator's point of the view:

- The organization should have a clear corporate policy in regard to stakeholder consultation, and the top management should be fully supportive.
- A transparent and fair approach is crucial. Public trust is hard-earned but readily lost.

- Consultation should begin as early as possible. Late involvement of the stakeholders (e.g., after key decisions have been made already) may be counterproductive.
- Technical advisors (the "champions" or "spokespersons") must be technically knowledgeable but should also be capable of communicating successfully with the public (and their management, of course). A facilitator may help cover the middle ground. This is a point of intercultural coordination.
- Coordination can be eased by one stable point of contact within the decommissioning organization—knowing your counterpart personally may help stakeholders feel involvement and ownership.
- Training can be required—in different forms- to upgrade communications either for local communities or nuclear operators or both in order to help each party reach a common culture for the purposes of the decommissioning-centered dialogue. This can be viewed as a form of socialization.

To end this section with an actual case study, one might refer to [23]. In 2010, the French Institute for Nuclear Safety and Radiation Protection (IRSN) ran a pilot project focusing on a nuclear installation safety case. It related to the decommissioning of a workshop at the La Hague fuel reprocessing site. The aim of this project was to test mechanisms for IRSN and some stakeholders (NGO's, elected officials, etc.) to interact in technical debates. The dialog served to introduce the stakeholders to the technical review process and hopefully provide input. The test proves that managing a productive dialog on technical matters between the nuclear organizations and miscellaneous stakeholders remains a serious issue. Especially troublesome was the issue that most expert reports were not publicly available; besides, there is a conflict between the opposite principles of transparency and confidentiality of information.

An extensive coverage of stakeholder involvement in decommissioning is given by Ref. [24]. See also Chapter 6 of this book.

3.5 Conclusions

Decommissioning is a dynamic process by nature and requires a range of behaviors and skills associated with dealing often with complex, participative, and adaptive changes. Cultural factors, including motivation, response to changes, attitude to new forms of collaboration and others, are imperative to the smooth progress of decommissioning. The following guidance highlights means to incorporate cultural factors in the project [25]:

- Be transparent: people should understand the rationale for change and how change is going to affect them;
- Provide authoritative (not authoritarian) leadership with the managerial skills and determination to realize change;
- Be firm about the mission and pursued outcomes;
- Communicate and seek support straightforwardly, consistently, and in a way acceptable to stakeholders;
- Instill a sense of belonging to all people and organizations involved, regardless of their original background and prospects;

- Make people sense wins by specifying early goals and outcomes that are within reach;
- Never give up—you need to foster assurance and resolution for yourself and (should) for others;
- Maintain a sense of readiness for changes; and
- Make intended long-term change last—to this end, changes made will have to be incorporated in cultures.

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Knowledge management toward, during, and after decommissioning

4

F. Borrman
iUS Institut für Umwelttechnologien und Strahlenschutz GmbH (Institute for Environmental Technology and Radiation Protection), Aschaffenburg, Germany

4.1 What is knowledge?

An IAEA report on nuclear knowledge management [1] lists no less than six different (and partially conflicting) definitions of knowledge. Obviously, the term knowledge is not clear even among the experts. In this chapter, knowledge will be understood as the total of human thoughts, feelings, experiences, and abilities with regard to a certain topic—in our case the decommissioning of nuclear facilities, comprising all attached and connected topics, such as clean-up activities for the release of sites.

When it comes to the explanation of knowledge the stepwise understanding of knowledge is widely used. Sometimes it is picturized as stairs and sometimes as a pyramid.

The steps of the stairs are defined as:

- *characters* as basic symbolic representations, such as the numbers one and eight. If these are brought into a useful sequence, this can be understood as
- *data*, such as "18°C." Such data packets can be linked to
- *information*, such as the statement, "the outside temperature is 18°C." This information as such has often no direct meaning, and it misses context. Only the context gives the applicability and validity of the data, such as the following revision: "In spring, day temperatures in Rome often exceed 18°C." This now can be understood as
- *knowledge*. It can be applied, for example, when choosing clothes for a trip planned to Rome in the spring.

Knowledge can be represented in three major forms:

- *explicit knowledge* (such as this book, which is written down and easily deployed),
- *implicit knowledge* (such as the thoughts of the authors of this book, which may contain more knowledge than is written down, but this part can only be accessed directly from the knowledge holder) and
- *tacit knowledge* (one who has this knowledge might not even be aware of having it; it can include a gut feeling or some tactile or other manual skills). Tacit knowledge can be transferred through training and apprenticeships.

Knowledge management is in this chapter understood as the systematic approach to plan for, identify, generate, develop, codify, apply, store, disseminate and forget knowledge as well as the necessary planning and controlling aspects.

Knowledge management is usually understood as an intra-organizational task. Some thoughts will be given later to show that this perspective may be too narrow in the field of decommissioning of nuclear facilities.

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4.2 What is knowledge management?

Knowledge management, as defined in the prior chapter, comprises a set of different tasks to ensure that the necessary knowledge (or critical knowledge) is available to an organization at any given time. The widely used knowledge management cycle according to Ref. [2] comprises the following tasks:

- *Planning* (What knowledge do we need? What do we have? How can we fill the gaps?)
- *Identification* (What knowledge do we have? where is the knowledge, and how can it be accessed?)
- *Generation* (How is knowledge generated–on an individual or collective level?)
- *Development* (How can the knowledge be developed in width and depth?)
- *Dissemination* (How can the knowledge be passed on?)
- *Application* (Conduct the main processes of the organization and apply the knowledge)
- *Conservation* (How can we ensure that the knowledge stays available and applicable?)
- *Assessment* (What is the state of our knowledge and what is the state of our knowledge management?)

This approach underlines that this is a task to be carried out on a constant basis and that it has a strong connection to other management cycles, especially the continuous improvement according to ISO 9001 [3]. The connection also makes clear that knowledge management cannot be a separated task, carried out by a single person dedicated to it. It is to be an integral part of the management system because it has direct implications on safety, HR (human resources), and many other fields and needs spreading throughout the company.

Other approaches, such as the eight-step knowledge management best practice model of Nuclear Decommissioning Authority (NDA) [4] focus on slightly different steps but also include a circular process for knowledge management.

To the understanding of the author, a knowledge culture needs to be established in the companies and in the mindset of employees at all levels of hierarchy to raise the awareness on the topic. This might even be more important in the field of decommissioning than it is for operation, because the need for knowledge sometimes may be less obvious and its connection to safety underestimated.

The performance of knowledge management systems is usually assessed by maturity models. These check the planned functionality against the achievements and the actual status of the management system.

It is vital to understand that knowledge management is an active task. Knowledge that is not used and not applied will be forgotten or turns useless as it outdates. In the field of semantic systems, this is often referred to as “gardening.” Going through the garden, snipping brown leaves and dry branches, watering or fertilizing what needs to grow, and cutting down what grows in the wrong direction is a good metaphor of knowledge management. Neither is it possible to keep a garden in shape without the effort of a gardener, nor is it possible to just store knowledge without working with it and expect it to be applicable when needed.

4.3 What makes KM in decommissioning different from KM in operations?

Decommissioning of nuclear facilities has come into greater focus during the recent decade. Nevertheless, it has a much older tradition and there is a whole range of fundamental changes when a facility is changing from operation to decommissioning:

- *Organizational changes*: A line organization is changed into a project organization. The aim of the organization is changed from carrying out a defined (operation manual, processes, procedures) process into a constant change process, the aim of which finally is the elimination of the organization itself.
- *Task changes*: Decommissioning fundamentally differs from operation. Major safety aims and functions cease to be relevant, while others become relevant.
- *Funding changes*: The organization's funding changes from a profit organization into a budget-driven one. This also implies that while the plant has most likely been a source of revenue during operation, it becomes a cost center in decommissioning.
- *HR issues*: Early retirements, brain drain to operational facilities, and the strong interactions with the supply chain as well as motivational issues are key. Operational personnel are not necessarily the best choice for decommissioning from a qualification point of view.
- *Supply chain interaction*: Specialized companies may not only carry out specialized decommissioning tasks but also have far more experience in decommissioning in general than the operational personnel.
- *Regulatory changes*: Changes in regulations and regulatory environment may also lead to new necessities for KM.
- *Change and configuration management:* During decommissioning, the status of the facility is no longer constant as it was during operation (when every action seeks to re-establish a stable operational condition), but there is a constant flow with the aim of the facility's elimination. Configuration management becomes a far more challenging task in decommissioning.

4.3.1 Organizational changes

The aim of the knowledge management during operations is to support an endless process, carrying out defined, highly repetitive tasks. Knowledge management support aims at controlling the relevant processes in depth and understanding the boundary conditions and process parameters to ensure that the process of energy generation (or fuel production or other purposes) can be carried out with high precision, reliability, and quality and in a safe manner.

In decommissioning, this changes to a clearly defined singular aim—the elimination of the plant and the disposal of any remaining radioactive material. In most cases there will be defined end states and acceptable activity levels for any remaining structure and areas. The support of Nuclear Knowledge Management (NKM) now aims at ensuring the relevant knowledge for many very different processes as well as skills, and tacit knowledge are available in the time these are needed.

4.3.2 Task changes

Besides these intra-organizational changes comprising structure and aims, also the nature of the tasks changes dramatically. While during operation the safety functions (control of reactivity, control of criticality, control heat removal, ensure confinement of activity and limit the doses to personnel and public to acceptable levels) are key, decommissioning focuses on controlling heat removal, ensuring confinement of activity and limiting the doses to personnel and public to acceptable levels. However, it also comprises separating the radioactive (activation, contamination) material from the matrix (systems and buildings) and dismantling, segmenting, and packing any resulting waste into the respective disposal containers. Mainly these are tasks that didn't play a major role during operation (of course, decontamination and clearance also are carried out during operation; nevertheless, their application in decommissioning is a quite different task).

It is very likely that the relevant knowledge is not available at the plant in the beginning of the decommissioning process. As said, one of the aims of decommissioning is to eliminate the necessity of an operational organization. Thus, the operational organization cannot easily maintain the knowledge of decommissioning because it is eliminated at the end of the decommissioning process. This makes cross-organizational transfer of knowledge an important task (to and from specialized companies in the supply chain, the mother company, and between plants belonging to the same mother company). It also implies the importance of cross-organizational and cross-national knowledge transfer, for example in communities of practice such as the IAEA International Decommissioning Network (IDN).

4.3.3 Funding changes

As the funding of the operational company changes at the same time from money-generating to money-consuming/budget-driven, relevant economic processes also change. The risks and opportunities from decommissioning significantly differ from operation. This also implicates that many auxiliary processes change. The funding changes will have an impact on the motivation of management and staff, on their reputation and standing within the mother company, and on their self-confidence. Additionally, this funding of a given budget often leads to the investment in "doing" rather than in "thinking". This might not pay off in the long run. In the case of knowledge management, planning for the task may keep companies from paying for recreation of knowledge lost at an earlier stage.

4.3.4 HR issues

Due to the changes in the tasks, some positions become obsolete. This comprises mainly the positions that are directly bound to reactor operations. Depending on the status of the facility at the beginning of decommissioning (removal of fuel, system decontamination, etc.), many functions will be obsolete. The respective personnel have very specific education and training that makes them valuable for other operational plants. On the other hand, the necessity to reduce personnel numbers in general will lead to early retirements and leaves.

A very important impact on personnel is motivation. The operational personnel have spent a good share of their professional lifetime on operating the plant (the usual lifetime of a nuclear power plant covers at least two professional lives). They have invested their skills, knowledge, and effort in optimizing the operations and increasing availability of the plant. Changing to decommissioning may indicate to many that previous efforts are obsolete.

On the other hand, because the final aim of the organization is to eliminate itself, thus eliminating the jobs of its employees, the staff may have the feeling that they are destroying their own jobs. This may result in mediocre performance (this may even not be a conscious decision but influenced by the feelings of the worker).

The lack of motivation resulting from these two reasons will also influence KM by influencingthe willingness to share knowledge and information.

4.3.5 Supply chain interaction

Decommissioning comprises many tasks that are not in the scope of an operating organization. Therefore, many specialized suppliers are engaged in decommissioning. Often the expensive specialized equipment (or its manufacturing on purpose) only pays off if it can be applied several times. These specialized tasks comprise, but are not limited to, the following:

- System decontamination
- Underwater segmentation and packing of the core and core internals
- Concrete segmentation (drilling, wire sawing)
- Characterization (in-situ measurement, waste package characterization, clearance measurement)
- Logistics (storage, in-house movements, conventional waste streams)
- Decontamination of parts (water jetting, abrasive jetting)
- Decontamination of buildings (wall and floor scaling or milling)

What these tasks have in common is that an exchange of knowledge and information is necessary that is beyond a usual exchange between supplier and employer. The exchange comprises on one hand knowledge on plant status (e.g., contamination levels, past incidents, materials used, operational history) and functionality (how has plant equipment been used, what requirements are there for replacements, what are the safety requirements). On the other hand, in-depth knowledge about the supplied tools, equipment, and services is required, such as functional and safety aspects, verification, and design features. Not all of the supply companies in this field have an extensive nuclear background and not all companies with the respective background can supply what is required for decommissioning.

It will be difficult for the procurement department to specify and to order specific tasks that have never been carried out yet in the plant (and never will be carried out again afterwards). Additionally, the companies specialized in decommissioning and dismantling may not necessarily be the ones with which the plant already has a qualified relationship.

4.3.6 Regulatory changes

The influence of the regulatory aspects is very much dependent on the regulatory framework in the country of application. In some countries (such as Germany) a separate decommissioning license is necessary in order to start decommissioning and dismantling. In other countries, lifetime licenses also cover the decommissioning phase.

In the first case, the regulatory impact may be greater because it is likely that the regulatory counterpart changes, as either different authorities or different departments of the same authority are competent compared to the authorities or departments competent for operation. In cases where a whole fleet is ceasing operation, for example, as a political phase-out decision is executed, the personnel of the regulator may also have to move from operation to decommissioning. This implies that also the regulator (or at least parts of its staff) may be unexperienced in decommissioning licenses or authorizations. The same may be the case for the technical support organizations (TSO). This can cause a lack of confidence from all parties engaged, which usually leads to a large conservatism in the application of safety and radiation protection that might not be adequate to the level of hazard resulting from the actions and the materials involved.

4.3.7 Change and configuration management

The plant status changes constantly (in some stages faster, in some stages more slowly). The aim of decommissioning activities is—if we exclude entombment—to eliminate the plant completely. This constant change may have plateau phases (for example, when considering deferred dismantling and the respective phases in safe enclosure) but will not stop before reaching the end state that is in accordance with its license implications.

An additional challenge is that all systems used for configuration management (e.g., an operational management system) may be not very useful for the purpose of operating a facility in decommissioning. The clear end of the decommissioning and the changes in funding will make the management hesitant to invest in additional information technology (IT) systems and especially in systems with the “exotic” touch of knowledge management systems dedicated for decommissioning. This importance of change and configuration management is not only a necessity for radiation protection and bookkeeping of radioactive materials but also for conventional safety aspects such as fire protection (changes in fire load may be necessary to be tracked on a daily basis). These changes also result in a documentation burden on the staff that is far beyond operational level. Together with the changes in the tasks, this leads to most of the plant personnel information workers having new responsibilities and roles.

All these changes on multiple levels make it evident that the KM system from operation will usually be unfit for decommissioning.

The good news is that a dedicated and streamlined knowledge management will not only help to understand the relevant tasks and make the right decisions in the right time and in an informed manner, but it will also give the staff the opportunity to carry out important work safely and with confidence.

4.4 What needs to be planned?

Implementing a decommissioning knowledge management system follows the principle as the implementation of the operational knowledge management. Knowledge mapping, knowledge analysis, and gap analysis are the common steps prior to the establishment of a system.

The difference will be—at least in cases where there is a direct change from operation to decommissioning—that there is an existing knowledge management system. Parts of the operational knowledge management system will be suitable also for decommissioning, parts will be adapted, and parts will have to be created while others are eliminated. In order to distinguish the four fractions, a proper planning process for the decommissioning KM system is inevitable. These existing parts may contain some pitfalls because they are designed and operated for another purpose. A critical review of the existing processes needs to be carried out systematically to determine the fitness for the new purpose. The portfolio of knowledge management methods will also require a critical review to ensure that relevant methods are readily available when needed.

As the nature of the undertaking changes from constant, virtually endless operation to a project with a defined end point, all knowledge necessary to reach this endpoint can be clearly defined, if the way to reach this end point is clear. Such a clear end point will be the encountered when decommissioning a standard NPP or research reactor without larger incidents or accidents during operation.

This may not be the case for large, complex sites, legacy sites, and postaccidental situations. In such cases, a decision tree can be elaborated, that is then followed throughout decommissioning (and perhaps environmental remediation). The decision tree will have many branches and end points in the beginning. With each decision taken, the decision tree will loose the branches not used and thus become narrower and clearer with each step. With each step carried out, each risk or uncertainty that can be eliminated reduces then the number of possible actions to reach the defined end state. In cases where no end point can be defined yet (e.g., the not uncommon case of there being no waste acceptance criteria for certain waste streams, due to either the lack of a repository or the lack of treatment pathways), interim stages will serve as holding points to be reached. The knowledge necessary is determined by the sum of all knowledge required to make informed decisions at the defined decision points. In such cases, the amount of knowledge to be preserved on the nature of former operation, the processes and procedures, the resulting waste and remaining structures may be significantly higher. This is caused by a higher level of uncertainty that needs to be covered and the additional knowledge that is required if several branches of the decision tree are to be kept alive. The nature of the repository will determine the knowledge necessary on certain waste ingredients as these may influence its safety case. If the nature of the repository is not defined yet, the knowledge also on minor ingredients must be kept, as it could turn out to be important at a later stage.

Examining the papers published and speeches given on decommissioning in an international context, one might come to the conclusion that these complicated cases are the majority of decommissioning projects. This is clearly not the case, despite the larger efforts and larger budgets that these cases require. But most decommissioning already is, and even to a larger extent will be in the future, a standard task in the life cycle of a nuclear power plant. Decommissioning is taken into account at much earlier stages of the lifetime of a nuclear facility. Experience gained from the complicated cases was transferred into the relevant IAEA regulations and, for example, WENRA (Western European Nuclear Regulators Association) safety reference levels and safety objectives.

In such easier cases, the end state is clearly defined by the licensing conditions or the decommissioning plan. This should be greenfield and a set of waste packages compliant with the acceptance criteria of the respective repositories. With this in mind, the steps and processes and the relevant knowledge to achieve the steps and conduct the processes can be assessed, the available knowledge examined, and an action plan deduced to fill the gaps.

An additional complication may in both cases result from the timescales involved. Decommissioning and environmental remediation may evolve way beyond the average work life and certainly the average turnover span of a worker or engineer. The waste package documentation resulting from the decommissioning and environmental remediation efforts may require storage for long periods of time. Usually the operator is not responsible for disposal of the resulting waste, but he or she needs to be aware of the requirements, the interfaces, and the timeframes involved in order to compile records that are acceptable for the repository operator. Therefore, decommissioning knowledge management needs to take into account three levels of timeframes: the short timeframe (months to years) for HR issues and knowledge capture and preservation, skill management etc.; a medium timeframe (years to decades) to cover the knowledge needs for the overall decommissioning project; and a long-range timeframe (decades to centuries) for the waste disposal knowledge (or at least the interfaces to it).

At any point of the planning phase the cost connected to the loss of knowledge can be estimated. In some cases, it might be a conscious decision to lose knowledge and to recreate it at a later stage because this might be cheaper than preserving tacit knowledge, especially, over long timeframes. The latter would require staff to carry out the respective tasks during the whole process in order to preserve this knowledge and hand it on to the next successor.

It is also worth considering "engineering out" the necessity of certain knowledge. This might be of special interest when thinking about a deferred dismantling strategy. It may be much better to eliminate all systems, structures, and components that require special knowledge for their handling or knowledge about their operational history. The remaining dismantling and decommissioning steps then can be carried out using standard procedures and technologies that can be assumed being available also in a distant time.

The planning should also take into account that knowledge management will require responsibility, accountability, organization, systems, personnel and time to be carried out. It is a common struggle to determine the cost-benefit ratio of knowledge management. Taking the backward thinking approach [5] might make this less difficult in the case of decommissioning.

4.5 What to consider when implementing knowledge management for decommissioning

Many of the changes coming with the change of the operational organization into a decommissioning project organization have a direct impact on the implementation and execution of knowledge management.

One of the most prominent aspects with regard to the employees will be the motivation. If decommissioning is carried out with operational personnel, their motivation to resolve decommissioning quickly might be limited because the end of the project might also end their jobs. Giving the affected employees a perspective beyond the project will be important at a very early stage, in order to reassure them that their personal career is in view of the company. This allows people to concentrate on the current tasks instead of being concerned about their own future. In terms of knowledge management, this can enhance their willingness to contribute and to share to a large extent. If knowledge management participation and knowledge sharing are brought into the personal performance indicators and are bases for incentives, this may also enhance the overall performance of knowledge management. If implementing personal targets on knowledge management, these need not only to be measureable, but they should also focus on knowledge sharing instead of knowledge acquisition.

This aspect is very much connected to a general openness in the company culture. In decommissioning, the operator has in most cases much less security concerns to care about than in operation. This will require a general change in the company culture. During operation, a great amount of security-related information is shared on a strict “need-to-know” basis. In decommissioning it may be worth thinking about reversing this and restricting only what needs to be kept confidential. Nevertheless, security implications on plants still in operation need to be taken into account. General approaches and security measures that are implemented in operational plants should not be revealed in order to prevent compromising security. It can on the other hand be negotiated with the authorities to remove many security measures as early as possible. This should in general be the case when the fuel has been removed.

Early retirement is often used to reduce the staff numbers at early stages. Staff, especially if in important positions, may understand this as a lack of gratitude and misunderstanding of their work during operation. This will influence the willingness of this staff to share their experience and to organize handover of information, knowledge, and professional networks. The latter is often underestimated and not taken into account for knowledge sharing. In many professional networks, individuals are granted reputation and respect depending on their contribution. A successor will neither automatically inherit the merits nor the personal relationships in the networks. Taking over networks will require meticulous planning and a larger timeframe to allow an introduction to the peers by the successor. Thus, it is important to coordinate personnel development plans, economic plans, and retirement plans with the necessities of knowledge management.

The organizational changes will need to be reflected in the knowledge management, especially in terms of accountability and responsibilities. Many project organizations and thus many decommissioning organizations are set up as matrix organizations. This can be a challenge when ensuring clear reporting lines and accountability. It is inevitable to ensure the accountability for knowledge management on an executive level; otherwise there will be a constant lack of funding and responsibility.

This matrix organization also has implications on the access to IT systems. Many roles now have cross-cutting functions, requiring access to many different IT systems. This may on one hand bring some difficulties to the IT departments in terms of granting and organizing access procedures. On the other hand, it usually means that the respective persons need to use many different accounts on different systems. Most of these will be expert applications, not built for these cross-cutting functions and thus not allowing the respective tasks to be carried out conveniently. Struggling with Excel tables used to collect the outputs of different systems is not uncommon. If setting up technical knowledge management systems, this will require some attention in order to optimize the access to relevant data. Highly interlinked systems that have the ability to build dashboards that can collect the outputs from various systems, such as semantic systems, will be advantageous. Customizable dashboards will allow the users to adapt to changing requirements and changing plant configurations. A general flexibility is certainly an important asset of any decommissioning management system.

The accountability and responsibility mentioned already are key success factors for knowledge management. Only if there is a clear responsibility on an executive level—either anchored within the company's policies or by external requirements—will knowledge management be understood as an important task requiring staff, time, and budget. It will then find its way through the company hierarchy by delegation of subtasks and responsibilities. This responsibility chain comprises the regular reporting, the review by management, and the formulation of corrective action.

Management commitment is strongly linked to this topic. Only if senior management and the executive level are actively supporting, applying knowledge management, and providing living examples for a knowledge culture will the knowledge culture be established in a company. Such a knowledge culture is at foremost an extended awareness for knowledge management at all levels. If every staff member is aware of the necessity of knowledge management and its benefits, the likelihood of losing important knowledge is far smaller. If management at all levels is aware of knowledge management, they will plan for the necessary provisions to ensure the availability of relevant knowledge. If knowledge management is part of the management by objectives process and will appear in staff target negotiations, its value on a personal level will be clear. If all of these are implemented, the management will be capable of making decisions in an objective, informed manner and processes will run more smoothly with all relevant information at hand.

A complication of knowledge management in decommissioning might be the lack of an addressee. To whom can lessons learned be reported if the project eliminates its organization in the end? If there is not a function of the mother company, the state, or overarching organizations, this lack of a counterpart will also deteriorate motivation. It is far more convincing to report lessons learned (which are not always the stories of glory and success) to an interested counterpart than to a report that has the clear dedication to collect dust on a shelf. Also, continuous improvement in such an environment will soon cause questioning about the purpose of improvement. A fleet approach of the mother company will be helpful there. Most operating organizations nowadays have understood the importance of lessons learned from decommissioning and the necessity to transfer the return of experience from one decommissioning project to other plants. All plants will face decommissioning sooner or later.

Looking at a wider picture one may come to the conclusion that some regulatory requirements may be helpful in this respect. If an operating organization only operates one plant, it will neither profit from the experience of others nor have interest to forward their own experience, for example, in communities of practice such as the IAEA International Decommissioning Network (IDN) or others. The requirement to report the overall decommissioning experience exists in IAEA guides but is only weakly implemented in most countries.

Even more difficult is the feedback of experience from decommissioning to operating plants. There are several topics that could bring additional insight from decommissioning projects, such as the changes in materials, wear, and aging of certain components that cannot be assessed with nondestructive methods. But how much effort can be required from a decommissioning organization to feed back findings (and look for such findings, that are not the aim of decommissioning) to operating plants?

Cost-benefit evaluations of knowledge management systems are not easily done on an overall basis. Best practice is to implement based on the Pareto principle, in other words, to implement the few functions with the most benefits first. This enhances the user acceptance and anchors the system in the management and makes further enhancements defendable.

Such an approach requires the identification of the critical knowledge that is necessary to conduct the decommissioning process in a safe and efficient manner and to identify the most beneficial parts. Knowledge mapping is one of the tools to identify the necessary knowledge for the project. The next step is to identify the possibility to find, obtain, and apply this knowledge. The more difficult it is to be obtained or sustained, or the less available it is in the supply chain; also, the more expensive it is to be restructured, the more valuable is the knowledge. Therefore its coverage in knowledge management is more beneficial.[1] Tagging the items in the knowledge map with indices for the value of the knowledge helps to understand the most valuable parts of the knowledge to be addressed. On the other hand, it must not be forgotten that there is other critical knowledge, for example, necessary to fulfill regulatory requirements. If such critical knowledge is completely relying on the supply chain (and the supply chain is aware of that fact) the price for the supply may very soon be dependent on the necessity to fulfill these requirements and the cost for noncompliance rather than on the real value of the service.

It should also not be forgotten that some aspects of knowledge management (e.g., skill mapping by yellow pages etc.) will pay off in very small portions, but they have value due to the high frequency of their application.

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[1] Looking from a purely scientific standpoint on knowledge management, the management and the content aspects should be clearly separated. In many implementations, there will be no full-time additional staff for knowledge management, but knowledge management will be an additional task or role for managers with other main subject areas. Therefore, a more pragmatic view is applied here that does not necessarily distinguish between the knowledge manager and the subject matter expert. Everyone is understood as having both roles. In practical implementations in IT systems, each topic covered and each function implemented will be bound to some cost. Thus the decision to implement a certain function will always be connected to the beneficial use of the respective content.

The acceptance by the users will very much depend on their personal benefit from the knowledge management. The more the knowledge management aspects are integrated in the management systems and the daily work, the more likely is acceptance (and actual benefit for the organization).

The knowledge mapping approach will be transposed into a prioritization and be concluded in a knowledge management program that is coordinated at the executive level. The program should take into account the decisions between owning the knowledge or buying in from the supply chain and stipulate a regular review of these decisions. Questions that should be reviewed include, but are not limited to the following:

- What knowledge is critical for operations today?
- What is the status of this knowledge?
- What is the storage place and method of this knowledge?
- How is this knowledge validated?
- What collaboration tools exist and how are the collaborators acknowledged?
- What knowledge will become critical for future operation steps?
- How will we fulfill the knowledge requirements in future?

A deeper insight in assessing the knowledge management efforts is given in Ref. [4].

It should also be acknowledged that decommissioning is also a part of the lifecycle where some of the knowledge acquired so far becomes a burden and obsolete. Identification of obsolete knowledge and its elimination should be a vital part of the knowledge management process. This ensures a focus on the essential part of knowledge for decommissioning and is required to free effort and capabilities to deal with future challenges. No knowledge should be kept without a validated future use.

The form in which the knowledge is available may also be taken into account in this process. If there is for example only raw data and paper reports available, the effort to structure, categorize, and catalog these may be assessed against the efforts necessary to reconstruct the necessary part of the knowledge. Sometimes the latter is preferable.

When deciding about future knowledge, the level of uncertainty about the future knowledge needs and the future status of the plant should be considered. It may be helpful to think about

- known knowns (topics the organization is aware of knowing),
- unknown knowns (things the organization may know without being aware of),
- known unknowns (missing knowledge the organization is aware of), and
- unknown unknowns (missing knowledge the organization is not (yet) aware of missing).

Known knowns and known unknowns are covered by knowledge programs and planning; the latter is also covered by risk management. Unknown knowns should be discovered during the process of knowledge mapping (if it is relevant knowledge). The unknown unknowns will remain as uncertainties. They can be covered only by the flexibility and the structured approach of the knowledge management system, which also allows dealing with new challenges.

While current knowledge management mainly applies forward thinking (what can we do, and can we do it better?) decommissioning knowledge management can also apply backwards thinking (what needs to be achieved, what are the steps, what do we need to know to achieve these steps) [5]. The main opportunity of doing so is to achieve a very straightforward and lean knowledge management approach, with a measurable outcome (either the next relevant step towards the end state was or wasn't achieved).

4.6 What interfaces need to be considered?

The complexity of decommissioning projects and the integration of many stakeholders underlines the necessity to determine and describe the necessary internal and external interfaces.

For the internal interfaces, lifecycle-wide approaches have been. While there are some recent developments to a lifecycle approach to nuclear knowledge management for design knowledge, the aspect of a lifecycle approach to the overall knowledge management has only been recently discussed.

The knowledge and information necessary for decommissioning not only comprises the operational experience. Frankly speaking, operational experience and operational history often are of limited interest. What is of interest is knowledge and information from the design and construction phases; some examples are materials used, masses, chemical compositions, as-built drawings. Because there is no direct interface between design and decommissioning, the knowledge and information needs to be forwarded during the phases in between.

A lifecycle approach of knowledge management needs to take the following into account:

- Necessary knowledge for all stages
- Necessary interfaces between all stages, also between stages that are not subsequent
- Necessary involvement of stakeholders at each stage
- Necessary knowledge on the interaction of natural and man-made features of Structures, Systems and Components (SSCs) and the site with the contamination
- Awareness for uncertainties and the associated risks (Fig. 4.1)

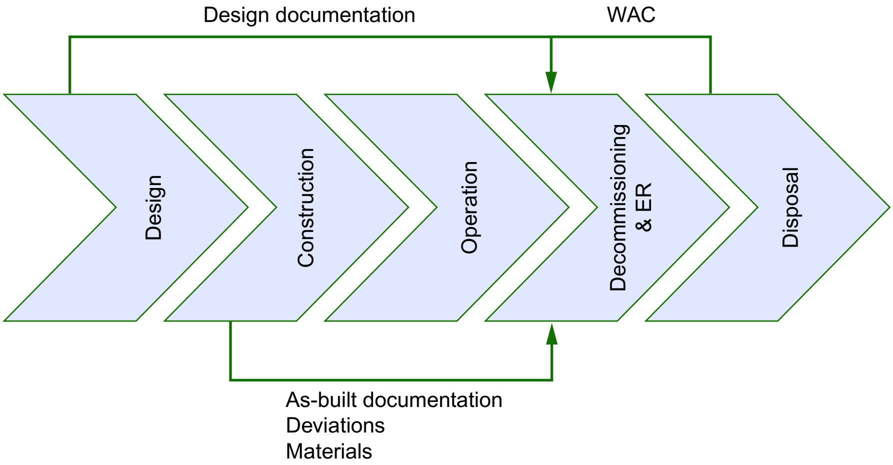

Fig. 4.1 Lifecycle approach to knowledge management [6].

Knowledge management also needs to describe the interfaces within the integrated management system (for example,to process, configure, and change management) and the handover processes between the phases.

Other interfaces are necessary from the decommissioning process to clearance and disposal processes. At least the latter will include the interfaces to additional entities, such as regulatory body and technical support organizations (TSO), and may address different timescales.

These processes will include information that is not relevant during the actual decommissioning process but only for these steps, such as chemical composition or activity distribution within a certain part. The knowledge management system needs to address these interfaces and information requirements to ensure that the necessary documentation can be developed in time and in compliance. This is of special importance because some of this knowledge (e.g., the underwater packing of core internals) cannot be easily recreated at a later stage, as the processes and tool implementations are gone and the resulting waste is inaccessible in grouted waste packages.

The regulatory interface in general needs some considerations because not only the counterpart will change (as described before), but also the information and knowledge requirements to be fulfilled. Processes and technologies will need to be described in more detail because the experience with decommissioning technologies on both sides is smaller.

The societal impact of decommissioning and radioactive waste management is also not to be underestimated. The interfaces to various stakeholders are important to be implemented and their information need to be reflected in these interfaces. In some cases, it may be important to transfer knowledge to stakeholder groups in order to allow them to make informed decisions and understand the overall decommissioning process. On the other hand, the direction from the stakeholder to the plant may also be important. The better the knowledge and information exchange process is planned and executed, the less surprises on both sides are likely to happen. Informed stakeholders will understand the decommissioning process and support the necessary decisions, if these aspects respect the necessities of the stakeholders.

In the case of a fleet approach, the coordinated transfer of knowledge between the projects needs to be orchestrated and organized and the relevant interfaces need to be designed into the knowledge management system. The value of the transfer will be higher, if the relevant parts of knowledge are easily accessible and applicable. Paper reports may not be the most beneficial way to do so. The use of fleet-wide wikis or other parts of the knowledge management systems may have a direct positive impact (and will in the same moment enhance the willingness to share because a direct attribution for sharing knowledge can be obtained).

4.7 How can technical systems look?

IT-based systems can be a great help for the implementation of a management system. It should be clearly distinguished between the technical system and the management system. The IT system is only a partial representation of the knowledge management system that will have limited value if the other parts such as knowledge culture, responsibility, and accountability are weakly implemented or not implemented at all.

On the other hand, this representation will usually be the interface to the daily work and will determine a wider part of the acceptance of the overall knowledge management system. Paper-based systems (or the electronic version in the form of a folder with the relevant documents) will usually not meet the expectations and needs of the information workers most of the decommissioning personnel represent.

The following key requirements have been determined, when implementing various systems:

- User acceptance and usability
- Agility
- Integration
- Cost efficiency
- Interfaces
- Data sustainability

4.7.1 User acceptance and usability

If designing technical systems such as portals, wikis, and dashboard applications, usability and training requirements are very important aspects. Whatever system is used in the end, the more familiar the staff is in its use, the more beneficial will the use be. Acceptance by users will very often be more dependent on the direct experience with the system than on overall sophistication of the system.

Thus, user friendly systems are a key element for KM. Any direct assistance that helps a user to conduct her or his daily work, such as autocompletion of fields (that does not only save the user time from typing, but it also helps avoiding typing errors) will bring direct and measurable benefit. Another important aspect is the conduction of repetitive work. This should be covered by adaptable dashboards that allow the user to fine tune the look and feel and, to a certain extent, also the conducting of the work.

Usability is defined in EN ISO 9241 [7] with the following aspects:

- Appropriate for the task
- Self-descriptive
- User-adaptive
- Error tolerant
- Conform to expectations
- Customizable
- Support learning

Most tasks in decommissioning are for information workers, but unlike in operation, their task level is often rather that of a generalist than a specialist. This needs to be taken into account when overtaking systems from operations.

4.7.2 Agility

As indicated before, the nature of decommissioning projects is determined by changes. Thus any IT-system needs to be able to cover these changes in an agile way. Fixed programmed databases will certainly not fulfill this requirement. The user should be capable to change not only the content, but to a certain extent at least the structures.

Because the standard user will not necessarily have the relevant programming capabilities, a metasystem is required that allows structural changes to be simple configuration changes. Semantic MediaWiki is one example of such a meta-system that can allow the user to change its own structure because it is self-referencing and the structure is defined via the standard user interface. Several modern semantic platforms follow the same approach.

4.7.3 Integration

The highly interlinked nature of decommissioning projects can be presented in systems that also feature a high level of linkage. Semantic data systems have increased in the last years to a level that allows their professional use and integration in business environments. The best knowledge management system is integrated in a way it is not even recognized directly as a separate system but directly woven into the business applications of the company.

4.7.4 Cost efficiency

Cost for the establishment of IT systems for knowledge management and especially for IT systems for knowledge management in decommissioning is always a difficult topic. Thus cost effective implementations following the Pareto principle (most benefit with the least effort) will be key. Early success stories need to be generated and communicated to overcome the general unwillingness to invest in such systems and to convince the budget holder based on the positive cost benefit analysis.

4.7.5 Interfaces

The system needs to cover the necessary interfaces described before, but it should also technically be capable to access existing data and systems to avoid any duplicate work. The more flexible such an approach to interfaces is, the better. Modern extract-transform-load-systems (ETL systems) have been designed for business integration applications, and they can allow a seamless integration in and interfaces to the existing business environment.

4.7.6 Data sustainability

The timeframes of the decommissioning project also need to find their ways into the IT system that is applied for knowledge management. This makes it inevitable to ensure accessibility of data, information, and knowledge also at later stages of the project. Open source systems have a clear advantage here compared to proprietary formats and systems [8] because they are better documented and source code is usually available.

The simpler the format, the easier it can be accessed in the future, even if the necessary software is no longer available.

4.8 Where can information be found?

Introduction to knowledge management itself can be found in the basic textbooks on the topic in general, for example, Refs. [2,9]; textbooks on organizational aspects [10]; or more specifically publications about nuclear applications [11]. A collection of practical aspects and applications in the nuclear industry can be found in [12].

IAEA has started various initiatives to take into account the importance of nuclear knowledge management especially in decommissioning. Inside the International Decommissioning Network (IDN) a working group on knowledge management in decommissioning has been established and is serving as a central collection point for knowledge management questions in this large community of practice. A practical outcome of this working group has been the integration of NDAs Sellafield knowledge management manual into the IDN wiki [13].

A Nuclear Energy Series report on the topic is in preparation by IAEA, bundling the efforts of the Waste Technology section and NKM section.

The British Nuclear Decommissioning Agency (NDA) has published a very useful and comprehensive guide on implementation of knowledge management, including the respective self-assessment [4].

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The real costs of decommissioning

5

T.S. LaGuardia
LaGuardia & Associates, LLC, Sanibel, FL, United States

5.1 Introduction

5.1.1 The need for accurate cost estimates

The interest in decommissioning seems to rise and fall, with multiple countries shutting down nuclear power plants (NPPs) for technical, economic, or political reasons; they sometimes shut down from panic following a major international accident. The nuclear industry began a nuclear renaissance of new plant orders and construction around the year 2010, but that slowed when economic forces such as the low price of competing natural gas became available. Instead a large number of NPPs were shut down for decommissioning prematurely even though the owner-licensee had insufficient funds set aside to completely decommission the NPP and dismantle it shortly after shutdown (the DECON or immediate dismantling strategy). This drove owner-licensees to re-examine the existing decommissioning cost estimates (DCEs) for accuracy and adequacy to safely decommission the facility. In many cases the DCE basis of estimate (BoE) had to be revised to reflect the "as shutdown" plant conditions and assumptions, and raising questions about uncertainties that perhaps were deferred in principle until the plant completed its full license life of 40 (and now 60) years.

5.1.2 Understanding estimate uncertainty

Uncertainties in cost estimation historically were treated differently by each cost estimator, and they may or may not have been clearly defined in the estimate. When the perceived implementation was a time decades into the future, not much attention was paid to these details. But now that the reality of premature shutdowns has become a near-term event, it is important to clearly identify and define the terms which were so loosely used in the past. Uncertainty is the umbrella term including allowances, contingency (sometimes called estimating uncertainty), and risks. These terms will be further addressed in this chapter because recent international efforts have developed a consistent set of definitions and their applications.

5.1.3 Historical efforts at cost estimate standardization

Interest in decommissioning cost estimation began in the late 1970s and early 1980s. The US Nuclear Regulatory Commission (NRC) contracted with Battelle Pacific Northwest Laboratory beginning in the late 1970s to prepare reference DCEs for pressurized water reactors (PWRs), boiling water reactors (BWRs), high temperature gas

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reactor (HTGR), and other nuclear fuel cycle facilities to provide guidance to the Commission on the cost of decommissioning so NRC regulations could be established to ensure funding. During the same years, the Atomic Industrial Forum (now Nuclear Energy Institute) contracted with Nuclear Energy Services, Inc., to prepare independent generic DCEs for PWRs, BWRs, and HTGRs. These early documents provided some guidance for standardization that served well in the early years of decommissioning funding planning. Later in 1986 the Atomic Industrial Forum contracted with TLG Services, Inc., to prepare a decommissioning cost estimating guidance document, "Guidelines for Producing Nuclear Power Plant Decommissioning Cost Estimates," [1], which was written for PWRs and BWRs, using a methodology of cost estimation that could be applied to any type of nuclear facility. These documents were principally used in the United States to develop DCEs for utilities to establish decommissioning trust funds (DTFs) for ultimate decommissioning. As interest in decommissioning grew internationally, several countries joined forces through the Organization for Economic Cooperative Development (OECD)/Nuclear Energy Agency (NEA), the International Atomic Energy Agency (IAEA), and the European Commission (EC) to develop a standardized format and content of DCEs.

5.1.4 Recent advances in standardization

In the late 1990s, the OECD/NEA and the IAEA solicited member states to contribute to the development of a standardized list of cost items for decommissioning any type of nuclear facility. The document known as the "Yellow Book" because of its cover was published with the intent of trying to create a standardized list for decommissioning cost estimating, and a standardized work breakdown structure (WBS). This document, while peer reviewed by the member states, was not widely adopted internationally. In 2005, the OECD/NEA, IAEA, and the EC jointly developed an updated version that included a more user-friendly document, a WBS dictionary, and guidance how to use the document in developing DCEs. The document, "International Structure for Decommissioning Costing (ISDC) of Nuclear Installations," was published by the OECD/NEA [2]. This document received much greater distribution and acceptance internationally, although the United States still has not fully embraced its application. One of the objectives of the ISDC document was to promote its use in benchmarking cost estimates against actual decommissioning costs.

5.1.5 The importance of benchmarking

Validation of cost estimates are an important part in demonstrating the achievable accuracy. This is best accomplished through the use of actual cost (AC) estimates from previously decommissioned facilities of similar size and function. There have been many nuclear facilities and NPPs that have been decommissioned in the past 20 years, but unfortunately, detailed AC information is often lacking. At best total ACs may be available to use in a comparison against an estimated cost, but that is generally difficult to achieve. The OECD/NEA has identified the importance of benchmarking in preparing DCEs, and it has established a new task to address this topic.

5.1.6 Problems obtaining the real costs

The problem in obtaining the AC of decommissioning for use in benchmarking stems from the proprietary nature of a contractor's work. Contractors are very protective of their trade secrets, estimating methods, project management procedures, and cost reporting abilities. Such things as cost or schedule overruns on a project will reflect poorly on a contractor and may affect the contractor's ability to bid future projects. Nevertheless, there is value in attempting to gather such real cost data for use in benchmarking.

5.1.7 Decommissioning funding history

Decommissioning funding has gone through a tortuous path throughout the development of nuclear energy internationally. During the early 1960s, the focus on nuclear energy was to develop NPPs and other fuel cycle facilities as quickly as possible including several variations of experimental and demonstration reactors. Decommissioning was rarely considered during these developmental stages. The thought was that "if we can build a reactor, we will be able to decommission it." The major eye-opener to the extent of the decommissioning liability occurred in the late 1970s, starting with the Three Mile Island Unit 2 accident in Pennsylvania. Preliminary estimates indicated the cost to recover from the accident and decommissioned the plant would be in excess of $1 billion. At the same time several utilities that were constructing new NPPs were feeling the effects of high interest rates on construction loans, and the potential threat of bankruptcy loomed over the project. The NRC recognized the potential volatility of financial assurance of all utilities it licensed to build and operate NPPs, particularly with respect to ultimately decommissioning them. In the early 1980s, the NRC initiated this program to require utility licensees to establish a decommissioning fund to safely shut down and decommission all types of nuclear facilities. This effort spread internationally in terms of the recognition of potential financial inadequacies to pay for safely dismantling nuclear facilities.

5.2 Funding adequacy

5.2.1 US NRC minimum funding amount

In the United States, the NRC requires licensees to provide assurance funds for decommissioning to be available when the plant is decommissioned. Before a NPP begins operations, the licensee must establish or obtain a financial mechanism—such as a trust fund or a guarantee from its parent company—to ensure there will be sufficient money to pay for the ultimate decommissioning of the facility.

Every 2 years, each NPP licensee must report to the NRC the status of its decommissioning funding for each reactor or share of a reactor that it owns. The report must estimate the minimum amount needed for decommissioning by using the formulas found in 10 CFR 50.75 (b),(c),(e), and (f) [3]. Licensees may alternatively determine a site-specific funding estimate, provided that amount is greater than the generic decommissioning estimate. Although there are many factors that affect reactor decommissioning costs, generally they range from \$300 million to \$400 million to remove the radioactivity above a free-release limit. Under the NRC rules, the nonradioactive systems and structures are not part of the license termination process, and the responsibility and cost of removal is left to the owner utility or licensee. Approximately 70% of licensees are authorized to accumulate decommissioning funds over the operating life of their plants. These owners—generally traditional, rate-regulated electric utilities or indirectly regulated generation companies—are not required today to have all of the funds needed for decommissioning, but these regulated generation companies are allowed to invest the DTFs in secure equities (stocks and bonds) that are expected to grow in value by the time the NPPs are ready for decommissioning. Any shortfall in DTFs compared to the estimated funds required for decommissioning can be earned by the investments in equities or bonds. The remaining licensees must provide financial assurance through other methods such as prepaid decommissioning funds and/or a surety method or guarantee. The NRC staff performs an independent analysis of each of these reports to determine whether licensees are providing reasonable "decommissioning funding assurance" for radiological decommissioning of the reactor at the permanent termination of operation.

The US NRC "Standard Review Plan for Decommissioning Cost Estimates for Nuclear Power Reactors," NUREG-1713 [4] provides the following guidance:

Licensees of operating nuclear power reactors must provide reasonable assurance that funds will be available for the decommissioning process. For these licensees, reasonable assurance consists of fulfilling a series of steps identified in 10 CFR 50.75(b), (c), (e), and (f). These steps assure that the licensee can certify that financial assurance is in effect for an amount that may be more but not less than the amount stated in the table in 10 CFR 50.75(c)(1). Specifically, this table states that if P equals the thermal power of a reactor in megawatts (MWt), the minimum financial assurance (MFA) funding amount in millions of Jan. 1986 dollars is the following:

(1) For a PWR: $\mathrm{MFA} = (75 + 0.0088P)$
(2) For a BWR: $\mathrm{MFA} = (104 + \mathrm{O}.009P)$

For either a PWR or BWR, if the thermal power of the reactor is less than 1200 MWt, then the value of P to be used in 1 and 2 is 1200, and if the thermal power is greater than 3400 MWt, then a value of 3400 is used for P. That is, P is never less than 1200 or greater than 3400. The financial assurance amounts calculated in equations 1 and 2 are based on Jan. 1986 data, and must be adjusted annually by multiplying 1 and 2 by an escalation factor (ESC) described in10 CFR 50.75(c)(2). This ESC is

$$\mathrm{ESC}\left(\text{current year}\right) = \left(0.65\mathrm{L} + 0.13\mathrm{E} + 0.22\mathrm{B}\right)$$

where L and E are the ESCs from 1986 to the current year for labor and energy, respectively, and they are to be taken from regional data of the US Department of Labor, Bureau of Labor Statistics; B is an annual ESC from 1986 to the current year for waste burial and is to be taken from the most recent revision of NUREG-1307, "Report on Waste Disposal Charges: Changes in Decommissioning Waste Disposal Costs at Low-Level Waste Burial Facilities," [5].

NUREG-1307 is updated from time to time to account for disposal charge changes. In Jan. 1986 (the base year), using disposal costs from DOE's Hanford Reservation waste disposal site, L, E, and B all equaled unity; thus the ESC itself equaled unity. A discussion of the origin of the 0.65L, 0. 13E and 0.22B terms is given in NUREG-1307. Thus,

$$\begin{aligned}\mathrm{MFA}\left(\text{in millions, current year dollars}\right) = {} & \mathrm{MFA}\left(\text{in millions, 1986 dollars}\right)\\ & \times \mathrm{ESC}\left(\text{current year}\right)\end{aligned}$$

NUREG-1307 provides several examples of how to determine the minimum decommissioning fund requirement using the above algorithm.

It should be noted that the coefficients in the ESC formula were taken from cost estimates prepared by Battelle Pacific Northwest Laboratory (BPNWL) for the NRC for Reference PWRs and BWRs. The coefficient 0.65 represents the percentage of the total BPNWL cost attributable to labor; 0.13 represents the percentage attributable to energy, and 0.22 represents the percentage attributable to disposal (burial). A site-specific estimate may have different coefficients.

5.2.2 International regulatory requirements

There are several methods that have been used internationally to create and maintain decommissioning funding assurance. The OECD/NEA conducted a survey of its member states of their current practices in cost estimation and funding titled, "Cost Estimation for Decommissioning," ISBN 978-92-64-99133-0 (2010) [6]. The report provided an international overview of cost elements, estimation practices, and reporting requirements. The survey respondents concurred that a funding plan was necessary and that they either had a plan in place or were developing one.

In some countries, the government provided the funding for decommissioning, but in most cases the utility was required to provide funding and could recoup its cost through electricity rates charged to consumers.

5.2.3 Site-specific cost estimates

The NRC formulas are primarily aimed at providing a simplified method to determine whether a utility/licensee had sufficient funds set aside to pay for decommissioning. However, site-specific factors often accounted for significantly greater decommissioning costs than predicted in the formulas. These site-specific factors need to be taken into account when developing decommissioning funding over the operating lifetime of an NPP. To accurately estimate decommissioning costs, the estimate must be based on the actual inventory of systems and structures installed at the NPP, the physical and radiological characterization of the facility at the time of shutdown, the management structure and labor costs of the utility and contractor (often referred to as the decommissioning operations contractor (DOC), or decommissioning general contractor), local crew labor rates, and equipment and materials needed to perform the work. In general, site-specific cost estimates are more representative of the costs to decommission the facility.

5.2.4 Decommissioning trust funds

To ensure adequate funds will be available at the time of decommissioning, United States and international regulations require that the funding be maintained in an external DTF. These funds are generally outside of utility licensee control so as to ensure that sufficient funds will be available to safely decommission the facility. United States utilities, whether regulated or unregulated, have the option of reporting the estimated costs for decommissioning using the NRC minimum funding amount, as discussed earlier, or using a site-specific cost estimate.

5.2.5 Regulated versus unregulated funds management

In the United States, several nuclear utilities established unregulated subsidiaries so they could compete with nonnuclear energy sources in the marketplace during the early 1990s. The term "regulated" used in this context refers to the individual state public utility commissions (PUCs; for in-state sale of electricity) that approve electricity rates that may be charged to consumers; or it can refer to the Federal Energy Regulatory Commission (for interstate sale of electricity), where electricity is sold across state borders to other utilities (wholesale electricity) for subsequent distribution to consumers. The term "unregulated" refers to utilities that have elected not to be subject to state or federal regulation of its rates and would rather compete in the open market against other forms of generation (coal, natural gas, or renewables). The NPPs associated with this unregulated market were called, "merchant plants." These early merchant plants proved to be highly profitable against coal fired plants and natural gas-fired plants up until 2012. After 2012 the price of natural gas dropped severely, making merchant plants unprofitable. The regulated nuclear utilities survived because they were granted a reasonable profit on the cost of service.

Both the regulated and unregulated NPPs collect decommissioning monies from each consumer through their monthly electric bill. Regulated utilities must report these incomes to the state public service commission as part of the filing for rate increases to its customers. Unregulated utilities are not required to do this, and they can use the funds as they see fit because the parent company has the financial resources to pay for decommissioning out of its operating funds. This is permissible under the NRC rules because the NRC staff performs an audit of the parent company's books to assure they are and will be solvent at time of final shutdown of the NPP.

5.3 International efforts to standardize cost estimates

5.3.1 Atomic industrial forum guidelines for cost estimates

By the mid-1980s many DCEs had been prepared for utilities seeking to provide guidance on funding amounts for future decommissioning. These estimates were prepared by several different cost estimating consulting companies, and no consistent methodology, content, or format was followed. It made comparing cost estimates from one utility to another or one NPP to another virtually impossible. The Atomic Industrial

Forum (now the Nuclear Energy Institute) recognized this shortcoming and initiated a study to provide guidance to the industry so that DCEs could be prepared in a consistent and well-documented manner. TLG Services, Inc., was selected to prepare this report entitled, "Guidelines for Producing Nuclear Power Plant Decommissioning Cost Estimates," [1]. The Guidelines document identified specific guidance for the methodology, structure, and content of a DCE. The methodology was based on a bottom-up approach, building on a detailed physical and radiological inventory of systems and structures for PWRs and BWRs using unit cost factors (UCFs; cost per unit of measure—$/cubic foot, $/ton, etc.). The guidelines addressed the decommissioning strategies of prompt removal/dismantling mothballing, entombment, and delayed dismantling following mothballing or entombment. DCEs prepared using these guidelines were well received by estimators, utilities, and regulators.

5.3.2 International structure for decommissioning costing

Cost estimation for the decommissioning of nuclear facilities has tended to vary considerably in format and content reflecting a variety of approaches both within and between countries. These differences do not facilitate the process of reviewing estimates and make comparisons between different estimates more complicated. A joint initiative of the OECD/NEA, the IAEA, and the EC was undertaken to propose a standard itemization of decommissioning costs either directly for the production of cost estimates or for mapping estimates onto a standard, common structure for purposes of comparison. The ISDC report [2] was published in 2012. It updates an earlier document published in 1999 and takes into account more recently accumulated experience. The ISDC aims to ensure that all costs within the planned scope of a decommissioning project may be reflected in the cost estimate. The report also provides general guidance on developing a DCE, including detailed advice on using the structure.

5.3.3 Cost control guide for decommissioning nuclear facilities

While the methodologies for cost estimation were improving in accuracy as the number of projects increased, the actual performance with respect to cost and schedule was not improving. In some cases costs were underestimated simply because the estimated database was inadequate or improperly applied. In other cases significant changes to the scope of work during the field implementation had a direct effect on the estimated cost. These changes were not captured by management nor reflected in the original scope of work and the original estimate. The disconnect severely hampers the ability to compare estimated costs to ACs, and the typical reaction was that the cost estimate was defective rather than acknowledging that scope change was a greater factor.

In other areas of construction, manufacturing, and government-funded projects, the need for a rigorous cost and schedule control system was readily identified. These industries developed a defined process by which projects would be managed, problems would be identified, corrective actions were documented, and the management team held accountable for project cost and schedule overruns. The system called the earned value management system (EVMS), relied upon a detailed breakdown of the project into a WBS, an organizational breakdown structure, and a responsibility matrix. Each of these areas were defined and then broken down into the various phases of the project for more concise control. This EVMS system has been adopted and endorsed by most of the internationally recognized standards organizations, including the Association for the Advancement of Cost Engineering International (AACEI), the Project Management Institute (PMI), the American National Standards Institute (ANSI), and the United States Department of Energy (US DOE), among others.

The EVMS effectively integrates a project's work scope, cost, and schedule into a single project management baseline (PMB) and reliably tracks the following

- Planned value of work to be performed, or the budgeted cost for work scheduled
- Earned value of actual work performed, or the budgeted cost for work performed
- AC of work performed
- Provides performance measures against the PMB
- Provides means of identifying, reviewing, approving, and incorporating changes to the PMB
- Provides trend analysis and evaluation of estimated cost at completion
- Provides a sound basis for problem identification, corrective actions, and management replanning

The OECD/NEA recognized the value of the EVMS process with respect to decommissioning, and it prepared a report describing how this process could be used effectively to control ACs in the field. The report, "Cost Control Guide for Decommissioning Nuclear Facilities," [7] was published by the OECD/NDA in 2013.

5.3.4 The practice of cost estimation for decommissioning nuclear facilities

The ISDC [2] focused on identifying all the elements of costs for a decommissioning project for any type of facility. The ISDC presents a matrix of typical decommissioning activities (organized in three hierarchical levels) and cost categories for each element in the ISDC hierarchy. Thus, the ISDC focuses mainly on using the cost itemization structure to ensure that all costs within the planned scope of a decommissioning project are reflected through the identification of all typical activities of any decommissioning project.

The OECD/NEA recognized the need for a document to describe the overall practice of decommissioning cost estimation. The objective of this guide was to provide a detailed process to describe quality estimates in terms of cost classifications, the BoEs, the structure of estimates, risk analyses of costs and schedules and contingencies, and quality assurance (QA) requirements followed by the licensee to ensure the estimate conforms to the requirements of its QA program.

The report, "The Practice of Cost Estimation for Decommissioning Nuclear Facilities," [8] was published by the OECD/NEA in 2015. The primary focus of this guide is on NPPs—both PWRs and BWRs. Although the guide mainly addresses single-unit sites, the approach is applicable to multiple-unit sites as well. With appropriate adjustments for physical and radiological differences, as well as nomenclature and process modifications, the guide may be applied to any nuclear facility including research reactors, fuel fabrication facilities, reprocessing plants, accelerators, or other sites

5.4 Detailed cost estimates

5.4.1 Elements of a cost estimate

There are five basic elements to a cost estimate: BoE, estimating methodology, structure of estimate, WBS, and schedule and uncertainty analysis. These five elements are described in detail in the following sections. The estimate must address the project scope as defined in the BoE. It must also address the out-of-scope activities, events, and cost drivers, which are generally probabilistic in occurrence.

5.4.1.1 Basis of estimate

The BoE forms the groundwork upon which the cost estimate is built. If the decommissioning plan or strategy has been selected, the objectives of that plan or strategy are identified in the BoE. Quality and accurate cost estimates must be based on the documentation and underpinning identified in the BoE. A typical list of items that might be included in the BoE is shown in the following:

1. assumptions and exclusions;
2. boundary conditions and limitations—legal and technical (e.g., regulatory framework);
3. decommissioning strategy description;
4. end point state;
5. stakeholder input/concerns;
6. facility description and site characterization (radiological/hazardous material inventory);
7. waste management (packaging, storage, transportation, and disposal);
8. spent fuel management (activities included into a decommissioning project);
9. sources of data used (actual field data vs. estimating judgment);
10. cost estimating methodology used (e.g., bottom-up, specific analogy);
11. contingency basis;
12. discussion of techniques and technology to be used;
13. description of computer codes or calculation methodology employed;
14. schedule analysis;
15. uncertainty and management of risk.

5.4.1.2 Estimating methodology

There are five recognized approaches to cost estimating:

1. Bottom-up technique

   Generally, a work statement and specifications or a set of drawings are used to extract (“take off”) material quantities required to be dismantled and removed, and UCFs (costs per unit of productivity—per unit volume or per unit weight) are applied to these quantities to determine the cost for removal. Direct labor, equipment, consumables, and overhead are incorporated into the UCFs. The process involves breaking the project down into its smallest work components or tasks, assigning the work into a WBS, estimating the amount of labor, materials, and consumables to accomplish each task, determining the duration of each task, and then aggregating the factors into a full estimate. Determining the overall duration in a bottom-up approach requires sequencing and resource leveling to be done as part of the scheduling process. A detailed breakdown into elementary work activities may also be done based on a detailed itemization of the cost estimate WBS.

2. Specific analogy

   Specific analogies depend on the known cost of an item used in prior estimates as the basis for the cost of a similar item in a new estimate. Analogous estimating uses a similar past project to estimate the duration or cost of the current project. Adjustments are made to known costs to account for differences in relative complexities of performance, design, and operational characteristics. It may also be referred to as ratio-by-scaling. Specific analogy estimating requires a detailed evaluation of the differences between a similar past project and the current project. Adjustment for these differences is an important element of this approach. It includes size differences, complexity differences, labor cost differences, inflation/escalation adjustments, and possibly regulatory differences.
3. Parametric

   Parametric estimating requires historical databases on similar systems or subsystems. Statistical analysis may be performed on the data to find correlations between cost drivers and other system parameters, such as units of inventory per item or in square meters, per cubic meters, per kilogram, etc. The analysis produces cost equations or cost estimating relationships (CERs) that may be used individually or grouped into more complex models.

   CERs that translate technical and/or programmatic data (parameters) about an activity into cost results. The algorithms are commonly developed from regression analysis of historical project information; however, other analytical methods are sometimes used. The models are very useful for cost and value evaluations early in the project life cycle when not much is known about the project scope. The models are dependent on the many assumptions built into the algorithms. Also, the validity of the model is usually limited to certain ranges of parameter values. For example, size differences of 100% between the past project and the current project would not be reasonable. Due to these limitations and constraints, it is incumbent upon the user to thoroughly understand the basis of a parametric model.
4. Cost review and update

   An estimate may be constructed by examining previous estimates of the same or similar projects for internal logic, completeness of scope, assumptions, and estimating methodology. This approach applies to updating a previous estimate to the current estimate and generally does not involve size difference considerations.
5. Expert opinion

   This may be used when other techniques or data are not available. Several specialists may be consulted iteratively until a consensus cost estimate is established.

Table 5.1 provides a comparative overview of the estimating methods and their advantages and disadvantages.

5.4.1.3 Structure of an estimate

The following structure applies for any type of nuclear facility. The same estimating approach is applicable, although the database of equipment and structure inventory would be specific to the facility.

It is helpful to group elements of costs into categories to better determine how they affect the overall cost estimate. To that end, the work scope cost elements are broken down into activity-dependent, period-dependent, and collateral costs as defined in the following paragraphs. Contingency, another work scope element of cost, may be applied to each of these elements on a line-item basis (as has been described separately) because of the unique nature of this element of cost. Scrap and salvage are other

Table 5.1 Estimating method comparison

Estimating method	Advantages	Disadvantages
Bottom-up	Most accurate because it accounts for site-specific radiological and physical inventory. Relies on unit cost factors (UCFs)	Requires detailed description of inventory and site specific labor, material, and equipment costs for the UCFs
Specific analogy	Accurate if prior estimates are appropriately adjusted for size differences, inflation, and regional differences in labor materials and equipment	Adjustments as noted may require detailed documentation and introduce approximations that reduce accuracy
Parametric	Suitable for use for large sites where detailed inventory is not readily available. Suited for order of magnitude estimates	Approximations based on areas or volumes introduce additional inaccuracies. There is no way to track actual inventory. Not suited for project planning of work activities
Cost review and update	Suitable for large sites where detailed inventory is not available. Suited for order of magnitude estimates	There is no way to track actual inventory. Not suited for project planning of work activities.
Expert opinion	Suitable when expert opinion of the specific work is available. Can be used for estimating productivity of smaller tasks based on an expert's experience	Expert opinion may not be specific to the work activities. May not reflect the radiological limitations of the project

elements of cost where noncontaminated materials may be recycled for reuse, but it must be clear what these terms mean and whether credit was taken for a cost reduction.

1. Activity-dependent costs

   Activity-dependent costs are those costs associated with performing decommissioning (hands-on) activities. Examples of such activities include decontamination, removal, packaging, transportation, and disposal or storage. These activities lend themselves to the use of UCFs (described later) due to their repetition. Work productivity factors (WPFs; or work difficulty factors (WDFs)—described later) can be added and applied against the physical plant and structures inventories to develop the decommissioning cost and schedule.
2. Period-dependent costs

   Period-dependent costs include those activities associated primarily with the project duration: program management, engineering, licensing, health and safety, security, energy, and QA. These are typically included by identifying the functions and services needed, including the associated overhead costs based on the scope of work to be accomplished during individual phases within each period of the project.
3. Collateral and special item costs

   In addition to activity- and period-dependent costs, there are costs for special items, such as construction or dismantling equipment, site preparations, insurance, property taxes, health physics supplies, liquid radioactive waste processing, and independent verification surveys. Such items do not fall in either of the other categories. Development of some of these costs, such as insurance and property taxes, is obtained from applicant-supplied data.

4. Contingency (estimating uncertainty)

Contingency is defined by the AACEI [9] as

> *a specific provision for unforeseeable elements of cost within the defined project scope, particularly important where previous experience relating estimates and ACs has shown that unforeseeable events that increase costs are likely to occur.*

The cost elements in a decommissioning estimate are typically based on ideal conditions where activities are performed within the defined project scope, without delays, interruptions, inclement weather, tool or equipment breakdown, craft labor strikes, waste shipment problems, disposal facility waste acceptance criteria changes, or changes in the anticipated plant shutdown conditions, etc. However, as with any major project, events occur that are not accounted for in the base estimate. Therefore, a contingency factor needs to be applied.

Early DCEs included a contingency of 25% that was applied to the total project cost. However, as the composition of the estimates changed over time the need for contingency also changed. More recent estimating models apply contingencies on a line-item basis, yielding a weighted average contingency for the cost estimate that describes the types of unforeseeable events that are likely to occur in decommissioning and provide guidelines for application. In general, line item contingency is preferred over bottom-line lump sum contingency, as it provides greater insight as to the degree of uncertainty.

Some estimators use probabilistic methods to determine contingency. This fact highlights the importance of describing how contingency was developed. Unless the estimator has specific experience in applying contingency percentages on a line item basis, the probabilistic approach provides a definitive basis to evaluate the uncertainties and contingency.

5. Scrap and Salvage

Scrap and salvage are the noncontaminated (clean) systems, components, and structures that may be recovered in a decommissioning project. In some countries the asset value may be used to offset (credit) the decommissioning cost (generally not a great amount), whereas in other countries it is not used as a credit.

Unit cost factors

The bottom-up cost estimating method lends itself to the use of UCFs modified by experience to account for work productivity (or work difficulty) factors. These UCFs are described in this section.

Cost estimating formula

Costs for repetitive activities (removal of pipe, valves, pumps, tanks, heat exchangers, ducting, electrical conduit and cable trays, concrete, and structural steel) are estimated by the following formula:

$$\text{Activity Cost} = \text{inventory quantity} \times \text{unit cost factor}$$

The inventory of each type of component is developed from the site-specific information for the facility.

UCF formula

The UCF is developed from a description of the activity to be performed, the estimated time to perform the activity under ideal conditions, the estimated productivity or WDF, the applicable crew composition and number of workers of each category, and the equipment and consumables required to perform the activity.

$$\text{UCF} = \left(\text{sum of labor cost} + \text{equipment and consumables cost}\right) / \text{unit quantity}$$

$$\text{Labor cost} = \left(\text{estimated time for activity} \times \text{WDF} \times \text{crew cost} / \text{h}\right) / \text{unit quantity}$$

$$\text{WDF} = \%\,\text{increase in time for the activity for the degree of difficulty expected}$$

The application of WDFs is intended to account for the productivity losses associated with working in a difficult or hazardous environment. The approach is widely used at operating power plants to account for difficulty in performing maintenance activities during outages. The application of this methodology to decommissioning activities is a natural and reasonable extension of this work adjustment factor.

1. Respiratory protection factor

   Respiratory protection factor is intended to account for the difficulty of a worker performing activities while wearing a full-face respirator or supplied-air mask. The respirator impedes breathing, obscures vision due to the mask window and fogging, and adds stress from the straps around the head. The respiratory protection factor can have a value of 10%–50%.
2. ALARA factor

   The ALARA factor is intended to account for the time spent preparing for an entry into a high radiation or high contamination area. This time is used to alert the crew to the potential hazards in the area, the specific activities to be accomplished while in the area, and emergency procedures to be implemented for immediate evacuation. This factor also accounts for the periodic training the crew would receive to maintain their radiation training and certification. The ALARA factor can have a value of 10%–15%.
3. Accessibility factor

   The accessibility factor is intended to account for difficulty of working on scaffolding, on ladders, in pipe tunnels, or in confined spaces. The limited degree of motion possible under these working conditions reduces the productivity of the worker. The accessibility factor can have a value of 10%–20%.
4. Protective clothing factor

   The protective clothing factor is intended to account for the time the worker needs to put on protective clothing for each entry and exit from a radiation-controlled area. Typically, this represents four clothing changes per day assuming suiting up in the morning, a morning break, a lunch break, an afternoon break, and the end of the shift. The protective clothing factor can have a value of 10%–30%.
5. Work break factor

   The work break factor is intended to account for the time a worker needs to take a morning break, a lunch break, and an afternoon break. Experience has shown worker productivity under stressful conditions improves when workers are allowed a morning and afternoon break. The work break factor can have a value of 5%–10% (nominally taken at 8.33%).

6. Work difficulty factor

   The WDF (also sometimes called work productivity factor) is intended to account for site-specific productivity differences in the workforce due to difficult working conditions or other factors. These differences may arise through union bargaining agreements, severe weather factors (heat or cold), or other limitations. The WDF adjustment is at the discretion of the estimator.

WDF for respiratory protection	10%–50% inefficiency
WDF for ALARA	10%–15% inefficiency
WDF for accessibility	10%–20% inefficiency
WDF for protective clothing	15%–30% inefficiency
WDF for work breaks	5%–10% inefficiency
WDF for productivity	Estimator's discretion

$$\text{Crew cost per hour} = \text{crew composition} \times \text{average hourly rate for each craft}$$
$$\left(\text{including contractor's overhead and profit}\right)$$

   Equipment and consumables:

$$\text{Equipment} = \text{the cost of small tools and equipment needed for the activity / unit quantity}$$
$$\text{Consumables} = \text{the cost of consumables needed for the activity/unit quantity}$$

   The database for development of UCFs is derived from actual decommissioning experience, other contractor experience, and reported results from successful decommissioning projects. Multiple UCF sets may be developed to account for the different WDFs needed for each activity.

7. Nonrepetitive activity cost estimates

   Nonrepetitive or unique activities, such as reactor vessel and internals segmentation, steam generator and pressurizer removal (for large NPPs), hot cell decontamination and demolition, and glove box decontamination and removal, are typically estimated using a crew man-hour and schedule duration methodology. Wherever possible, licensees should make use of their own experience, ideally that from decommissioning activities or alternatively derived from relevant major maintenance or renovation projects. Data may also be available from other relevant projects internationally. Lastly, data may be available from other countries. In all cases, where estimates include data drawn from other projects or experience elsewhere, the applicability and implications for the specific DCE should be discussed.

Some guidance on the duration of these specialized activities may be extracted from reports of actual reactor vessel and internal segmentation activities at large and small power reactors. In Belgium, the BR-3 reactor decommissioning may provide some data. In Japan, the JPDR decommissioning was well documented. In Germany the Gundremmingen Unit A reactor vessel segmentation was also well documented, and some of the more recent German NPPs decommissioned. In the United States, the decommissioning projects of Yankee Rowe, Connecticut Yankee (CY), Maine Yankee, and Big Rock Point were well documented. Similarly, activity durations for removal of steam generators and pressurizers may be extracted from actual records of the successful removal and disposition of the Gundremmingen Unit A and the US Trojan and Rancho Seco units

Unfortunately, specific data on crew-hours may not be generally available for proprietary data reasons, and the estimator can at best compile an estimated crew size and composition (supervisors, foremen, craftsmen, equipment operators and laborers) and apply any actual duration information derived from the literature. As new and updated information is received from similar projects, validated data should be incorporated into this cost estimating methodology periodically.

5.4.1.4 WBS and schedule

The WBS is used to categorize cost elements and work activities into logical groupings that have a direct or indirect relationship to each other. The work groupings are usually related to the accounting system or chart of accounts used for budgeting and tracking major elements of the decommissioning costs.

1. WBS levels

   The WBS elements are generally arranged in a hierarchal format. The topmost level of the WBS would be the overall project. The second level would be the major cost groupings under which project costs would be gathered. The next level would be the principal component parts of each direct or indirect cost category for that cost grouping. Subsequent levels are often used to track details of the component parts of the grouping so that a clear understanding of all the cost bases can be made.
2. WBS dictionary

   The WBS should include a WBS dictionary that describes the associated activities performed or events occurring in the decommissioning program.
3. Chart of accounts

   The project management or accounting software used on major projects usually identifies categories of costs in terms of a chart of accounts. The chart of accounts is where the individual cost items of labor, equipment, consumables, capital expenditures, recycle services, transportation, or disposal services are budgeted and cost-controlled on a rigorous basis. The EC, OECD/NEA prepared a "Standardized List of Definitions for Cost Items for Decommissioning Projects." This document was recently revised and replaced with the "ISDC." This document may be used to establish this chart of accounts.

Project phases

Decommissioning projects are usually performed in phases or periods describing specific activities of work. Typically, three phases are identified for immediate dismantling: predecommissioning planning, decommissioning and dismantling activities, and facility and site restoration. The ISDC provides a breakdown of decommissioning into phases that have been paraphrased and/or modified herein. The following paragraphs describe typical decommissioning project phases of work upon which the WBS is built.

1. Predecommissioning planning

   The preplanning phase of the project, which can be early even before the facility is permanently shut down, involves the preliminary assessment of decommissioning options, conceptual cost estimates and schedules, waste generation and disposition estimates, and exposure estimates to workers and the public. The objective is to select a decommissioning strategy and funding approach that will meet the applicant/licensee needs and satisfy regulators. During this phase detailed engineering evaluations are performed on the methodologies and technologies to be used for decommissioning. This phase includes interaction with regulators and stakeholders for acceptance of the approach, particularly the proposed facility end-state.

Facility decommissioning follows deactivation, that is, after shutting down operations and removing legacy wastes such as large quantities of high risk, readily accessible radioactivity (spent fuel, sealed sources, etc.),or highly hazardous reactive chemicals such as bulk quantities of acids and bases. After shutdown the residual radiological and hazardous material will be stable and can be inventoried by measurement and calculation. This site characterization phase is critical to identifying the scope of work to be performed. If the applicant/licensee elects to subcontract the decommissioning management to a DOC, the applicant/licensee will solicit bids from prospective DOCs and select the DOC to perform the work.

2. Decommissioning and dismantling activities

   This phase is the actual hands-on activities for decommissioning. It may also involve decontamination, removal, packaging, transportation, and disposal or storage of systems and structures to meet end-state objectives. For example, for a NPP, this would include removal of the steam generators, pressurizer, reactor coolant pumps, reactor vessel and internals, all safety related systems and structures, the turbine-generator, condensate system, feedwater systems, water cooling systems, fire protection systems, and finally building dismantling. For fuel cycle facilities, this would involve the removal of the main process systems and equipment.

   A final site survey will be performed to ensure all residual radioactivity has been satisfactorily removed to meet license termination criteria. Note that timing of this may be a sequential activity: one might declassify equipment, rooms, and buildings at different stages of the decommissioning project, with a final site survey coming at the end of all other operations involving radioactivity.

3. Facility and site restoration

   During this phase redundant buildings and structures are dismantled and demolished, and the site is prepared to meet the desired end point state.

   The reuse of facilities following decommissioning to conserve natural resources and to take advantage of the site infrastructure of equipment and structures may be included if it is specified in the decommissioning plan. It should be so noted in the list of assumptions as to whether reuse of specific facilities was to be included or excluded. Reuse of specific facilities is not truly a decommissioning activity. Unless there is a cost credit accrued to decommissioning in the form of an income source or sale of property, it is generally not included in DCEs.

Project management approach

The management organization is the applicant/licensee staffing assigned to the administrative and technical oversight of the project. In general, it may include the project-specific management organization and the licensee-support organization. The project-specific organization would cover the functions of project manager (and typically assistant project manager) and technical managers (engineering and planning, cost and schedule control, and waste management). The licensee-support may include the routine functions of health physics and radiological protection, QA, and operations and maintenance. The licensee-support may also include administrative managers (security, personnel/human resources, financial/accounting, public relations, janitorial, and others); below these levels are typically the superintendents in each discipline who oversee the subcontractor crews performing the work in the field or in the field office.

If the applicant/licensee elects to self-perform (sometimes called self-direct) the field decommissioning work, they may “subcontract” the field work to an in-house division, which then provides its own project management staff, with comparable levels as above. The subcontracted group will report to the applicant/licensee organization above. If the applicant/licensee elects to subcontract the field work to an external DOC, the DOC will establish a separate and distinct management staff to supervise the field work, appointing a Project Manager and all supporting personnel.

Some estimates separate the management organization from the hands-on work because most management contracts (or subcontracts) are on a level-of-effort cost basis (i.e., the organization is reimbursed for all its costs plus a fixed or incentive fee).

5.4.1.5 Uncertainty analysis

Uncertainty is the umbrella term including allowances, contingency (sometimes called estimating uncertainty), and risks. The importance of this topic of cost estimation has only recently been recognized in the industry. There is a great deal of confusion and misinterpretation associated with its use, and the next section provides an in-depth explanation of this topic.

5.5 Uncertainty in cost estimation

Uncertainty is the umbrella term including allowances, contingency (sometimes called estimating uncertainty), and risks. Former US Secretary of Defense Donald Rumsfeld described uncertainty as follows:

- There are known-knowns—things we know that we know
- There are known-unknowns—things we know we don’t know
- There are unknown-unknowns—things we don’t know we don’t know[1]

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[1] A phrase from a response US Secretary of Defense Donald Rumsfeld gave to a question at a US Department of Defense (DoD) news briefing on Feb. 12, 2002 about the lack of evidence linking the government of Iraq with the supply of weapons of mass destruction to terrorist groups.
Rumsfeld stated:

> *Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones.*

The known-knowns are used to develop the base cost estimate (sometimes called the Baseline Cost Estimate) and include allowances. These costs are fully expected to be spent.

The known-unknowns represent the contingency (estimating uncertainty). These costs are also fully expected to be spent.

The unknown-unknowns are the risks that are not certain to occur, or whose values are uncertain. These costs may or not be spent.

The following sections describe these terms and how they relate to the estimate to fund a project.

The OECD/NEA, IAEA, and the EC jointly worked to address uncertainty in a comprehensive and dedicated manner. It is a work in progress, but one of the most significant developments was a chart showing the relationship of project *in-scope* and *out-of-scope* uncertainties as they relate to the project baseline cost and funded risk. These relationships are shown in Fig. 5.1.

The figure shows the *in-scope* costs that make up the project baseline estimate to consist of the base cost plus allowances, as defined in the BoE, and the *in-scope* estimating uncertainty (also called contingency). These costs are fully expected to be spent. The *out-of-scope* uncertainties include the funded risk (developed from a quantitative risk analysis of the post mitigated risks) and the unfunded risk (the probability of occurrence deemed too low to include in the funded risk amount). This latter upper band is considered the *risk appetite,* the amount of risk the owner/licensee is willing to accept when funding the project. The meanings of these terms will be addressed in the following sections.

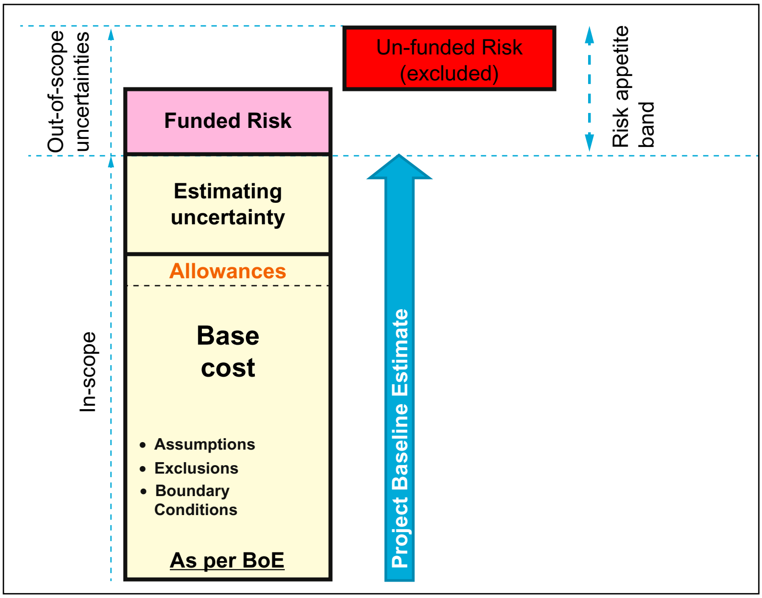


Fig 5.1 Elements of a decommissioning cost estimate.
From NEA/OECD, Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities, www.oecd-nea.org, 2017 (forthcoming).

5.5.1 Allowances

Allowances are estimates for items or tasks that need to be included but whose cost is not currently known. Such things as the cost of special tooling to segment RVs and RVIs won't be known until vendors can quote on the equipment. The estimator's best available information is used as a "placeholder." Allowances are included in the base cost estimate.

Allowances are considered known-knowns as the funds are certain to be spent, and they will be "trued-up" as the estimate matures.

5.5.2 Estimating uncertainty (contingency)

The AACE offered guidance on contingency as follows:

> *A specific provision for unforeseeable elements of cost within the defined project scope, particularly important where previous experience relating estimates and actual costs has shown that unforeseeable events that increase costs are likely to occur.*

The OECD/NEA, IAEA, and the EC decided the term "contingency" was too general and could include any amount of funding above the base cost. Therefore, they chose the term "estimating uncertainty" instead, which is used in the same manner for events that occur in the field that will increase costs.

This definition introduced the concept of events *within the defined project scope*, thereby bounding the types of uncertainty that would be considered in the project baseline cost estimate. For many years a percentage contingency approach was used and was accepted by owner/licensees and regulators. Because contingency costs are expected to be fully spent (and practice has shown that to be true), it is considered a known-unknown.

This definition was adopted for the ISDC. The AIF/NESP Report included 15 categories of contingency and provided typical percentages as shown in Table 5.2:

5.5.3 Risks

Because funding provisions covered 40 years (and now 60), it was realized there were events that could occur *outside the project scope.* However, they were not certain to occur, and the cost impact was not predictable. These are the unknown-unknowns. These events are determined by risk analyses, a quantitative probabilistic approach to estimating.

Risk analysis is a means of dealing with decommissioning project problems that extend beyond the project scope, the risk potentially causing an increase in cost or an opportunity potentially resulting in a decrease in costs. Risk analysis has become an integral part of cost and schedule estimating in recent years.

Contingency, as defined earlier, addresses problems within the defined project scope, such as delays caused by inclement weather, interruptions caused by late delivery of equipment and supplies, on-site industrial accidents causing project stand-down for safety investigations, tool or equipment breakdown, craft labor strikes, waste

Table 5.2 **Typical contingency categories and percentages**

Activity category	Percent	Remarks
Project management, engineering	15	Additional scheduling; attrition
Owner licensee and DOC staff	15	Schedule changes; insurance, taxes and permits
Decontamination	50	Low DFs, additional decon, chemicals
Contaminated component removal	25	Tool breakdown, special crews, consumables
Contaminated concrete removal	25	Stronger concrete, special equipment
Large component removal	25	Delays in special equipment; weather
Reactor vessel and internals removal	75	Tool breakdown, cutting, cask delays
Reactor packaging	25	Extra shielding, loading, cask delays
Reactor shipping	25	Weather, permits, road transit delays
Reactor burial	50	Surcharges—curies, weight, handling
Conventional LSA packaging	10	High void fraction, additional containers
Conventional LSA shipping	15	Weight/width/height restrictions, longer routes
Conventional LSA burial	25	Special handling, documentation
Clean component removal	15	Special access/handling; longer routes
Supplies consumables	25	Additional quantities, faster consumption

shipping problems such as improper documentation or vehicle road safety concerns, or unanticipated plant shutdown conditions. These conditions are handled by a contingency line-item percentage based on experience, or a single value percentage on a bottom line cost.

Risk analysis addresses problems that are beyond the project scope, such as a change in regulations regarding worker exposure limits, site release limits, waste transportation and a change in waste disposal acceptance criteria, an extraordinary increase in costs for labor, equipment and consumables, exceptionally difficult decontamination campaigns, extraordinary difficult remote vessel internals segmentation campaigns, or delays caused by stakeholder intervention. These conditions are handled by a risk analysis as discussed herein.

Some estimators include contingency as part of the baseline estimate in-scope costs because these costs will be fully incurred. Risk analysis is then used to deal with the out-of-scope conditions. Other estimators combine the in-scope and out-of-scope problems in its risk analysis, and risk analysis is used to specify the amount of contingency. In either case, it is crucial to identify how contingency and risk are being applied.

The elements of a risk analysis generally consist of four parts, sometimes leading to an assessment or estimate of project contingency as discussed earlier. In general, the quantitative risk management process involves those parts and associated activities for each new or existing project of major financial value. The four parts are as follows:

- qualitative (risk register);
- quantitative (Monte Carlo analysis);
- sensitivity analysis of major cost drivers; and
- cumulative probability curve.

5.5.3.1 Qualitative risk analysis

1. Assemble a risk management workshop of personnel familiar with the project.
2. Develop a qualitative risk register of all potential risks (negative outcomes) and opportunities (positive outcomes) by the following:
    - describing the potential risks/opportunities;
    - assigning a probability to each risk/opportunities;
    - assessing the severity should the risk/opportunity occur; and
    - giving each risk/opportunity a score (probability times severity).
3. Plan how you will prevent risks happening (or manage them if they occur). The highest scoring risks need to be considered and planned for in more detail.

    This is often referred to as "risk mitigation," where specific technological, administrative or financial measures are taken to eliminate or reduce the risk. Such actions prompt changes to the Baseline Cost Estimate to increase it or decrease it accordingly. The "residual risks" are then analyzed quantitatively as described in the following section.

5.5.3.2 Quantitative risk analysis

Quantitative risk analysis is a method of quantifying risks in order to determine the probability of achieving cost and schedule objectives and should be considered when (but not limited to) the following is true:

- projects/estimates that require a contingency reserve for the schedule and budget;
- large, complex projects require “go/no go” decisions (the “go/no go” decision may occur multiple times in a project); and
- projects/estimates where upper management wants more detail about the probability of completing the project on schedule and within budget.

There are many quantitative risk analysis tools and techniques, such as the following:

- scenario analysis;
- decision-tree analysis;
- Monte Carlo analysis;
- sensitivity analysis; and
- optimism bias.

In recent years, Monte Carlo analysis has become a popular choice; it is a risk modeling technique that presents both the range, as well as the expected value, of the collective impact of various risks. It is useful when there are many variables with significant uncertainties. It can be a useful technique but expert advice is required to ensure it is properly applied, especially when risks are not independent of each other. Before undertaking or commissioning such an analysis, it is useful to know how data will be fed into the model, how the results will be presented, and how decisions may be affected by the information generated.

In addition, specific care needs to be taken when trying to analyze changes to the baseline assumptions or a manifestation of remote probability risks with very high consequences, for example, early site shutdown and widespread contamination. These types of events would normally present themselves as a complete change to the fundamental premise of the baseline plan and as such cannot sensibly be incorporated into a statistical risk model centered on a plan with defined start and end points built up using a predetermined suite of baseline assumptions, which is the case within the funded decommissioning program or FDP (normal station operations and closure).

Typically this type of event must be treated as a scenario rather than a contingency provision, complete with a high-level plan of what this scenario may look like if it occurred and what the cost consequences would be, because the assumptions and their impacts will change any distribution profiles. This will result in a different cost probability distribution compared to the normal closure case. This would be particularly apparent if say the early closure was a consequence of a major plant event that significantly increased the complexity and costs of decommissioning the site. Once a scenario has been developed the gap between the baseline plan and the scenario could be utilized to underpin any quantitative analysis.

In summary, there is no right or wrong method, and in fact it could be viewed as more of an art than a science. However, irrespective of the chosen technique, the critical factors required are to clearly document the purpose or expectation of the analysis, how the chosen method meets that expectation, and also to demonstrate a clear relationship with the estimate, assumptions, and risk register.

5.6 Benchmarking decommissioning costs

There have been many successful decommissioning projects reported in international literature, from which many lessons have been learned. However, there is a scarcity of reliable AC data reported from these projects to use in comparing or benchmarking estimates against ACs. In some cases the cost data is not accurately recorded, and in other cases the information is deemed proprietary to the decommissioning contractors and the owner-licensees. This section provides a discussion of these issues and caveats for overreliance on comparisons to international experience. Often, the costs are reported in different year's monetary value, with or without inflation/escalation, and from different sources. At best, such comparisons can provide an order-of-magnitude basis of an estimated cost versus actual experience. Nevertheless, benchmarking has value if the appropriate precautions identified in this section are observed.

5.6.1 Difficulty obtaining accurate real (actual) costs

Comparing cost estimates against ACs is challenging because the ACs are rarely reported in the same format as the estimated costs. The scope of work estimated is often changed as the actual field work progresses to take into account changed site conditions, regulatory issues, contract arrangements, and management redirection of the project. In most cases, the AC reported in the literature will be the total cost with very little or no breakdown into its component costs.

The OECD/NEA report, “The Practice of Cost Estimation for Decommissioning of Nuclear Facilities,” [8] indicates that, when comparing costs, “cost figures should not be taken at face value unless these ten elements and their history are specified in comparative tables.” The ten elements are the following:

- Scope of work through to the end-point of the site
- Regulatory requirements, including details of reporting and clearance levels
- Stakeholders’ demands
- Characterization of physical, radiological, and hazardous material inventory
- Waste processing, storage, and the availability of ultimate disposition facilities
- Disposition of spent fuel and on-site storage prior to emplacement in a deep repository
- Clean structure disposition and disposal of the site for new developments
- Contingency application and use in the estimates
- Availability of experienced personnel with knowledge of the plant
- Assumed duration of the dismantling and cleanup activities

Not all of the foregoing criteria may be available for comparison. Estimators from other organizations or countries may use differing formats for presentation of the assumptions and cost data, and they may reflect site-specific or country-specific regulations, stakeholder interests, and end-point criteria. This was one of the driving reasons why the OECD/NEA ISDC was developed.

Cost estimation for difficult tasks, such as reactor vessel internals segmentation and vessel removal, is a difficult job. Obtaining detailed information from past experience is further complicated by the reluctance of past project managers to reveal proprietary information of either subcontractors or other vendors. Often the response will be, “We completed the job within budget,” not revealing that the segmentation subcontractor may have absorbed cost overruns on the project to avoid the embarrassment of exposing poor bidding practices. Searches of published reports, articles, and even regulatory documents may be similarly misleading.

5.6.2 Sources of AC data

The owner/licensees of NPPs are probably the best source of AC data. However, by contract agreements with contractors performing the work, such cost information is often proprietary information and cannot be released to the public. If the contractors bid their work on a fixed-price, lump sum basis they are generally not required to provide any detail of the cost breakdown. Fixed-price contracts are beneficial to the owner/licensee because they limit cost risks but do not reveal the true cost of the project. Contractors are reluctant to reveal whether they overran their budgets and schedules because of the obvious impact on their reputation in the industry. Other types of contracts such as cost-plus-incentive-fee are more revealing of the true costs of a contractor’s project work performance.

In the United States, the Electric Power Research Institute (EPRI) has been actively collecting information of decommissioning projects for its members. The reports produced by EPRI generally have a good description of what work was performed, a summary of actual *reported* costs and schedule, and lessons learned for the experience. These reports are available to EPRI members at no cost, but they are available to the general public for a significant fee.

In some cases where decommissioning ACs have exceeded their previously approved funding level, regulated utilities have had to seek additional funding from the state PUCs. They have often had to reveal how much was spent to date and how many additional funds may be required. Depending on the state PUCs, this cost data may be made public information.

The US NRC as part of its program to assure adequate funds are available before beginning decommissioning requires its licensees to submit biannual updates of estimated decommissioning costs. Five years before shutdown of the NPP a detailed site-specific cost estimate must be submitted along with assurance that full funding will be available upon NPP shutdown for decommissioning. The US NRC allows some field work to be accomplished towards decommissioning as long as there are no unreviewed safety questions that were raised. The licensee may then report how much of its DTF has been spent up to the point when the licensee submits its license termination plan for approval to continue decommissioning. This information may be available through the US NRC's public document room sources.

Lastly, some AC information may be presented at public conferences and workshops. But all the earlier mentioned precautions regarding accuracy should be observed in relying on these technical papers or presentations.

5.6.3 Scope of work differences

The most difficult factor in comparing estimates is the differences in scope of work. As noted earlier, at the time an estimate is developed the scope of work may be based on an assumed decommissioning strategy (immediate dismantling versus safe storage), then-known conditions at the site, radiological characterization of the NPP, and assumed end-state conditions after decommissioning. All of these items can change during the last few years of operation causing a significant change in costs. A cost estimate has to be considered a living document, changing as the scope of work and assumptions change throughout the NPP life.

5.6.4 Plant size and complexity differences

Clearly, plant size and type have a major impact on the decommissioning costs, and these factors need to be taken into account when comparing cost estimates and ACs. One cannot compare a PWR to a BWR, or a 600-MWe NPP to an 1100-MWe NPP. But within the same type or size category, comparisons may be made if the differences are accounted for properly. Within a close size range, comparisons may be made by adjusting costs using the cost estimator's approximation relating costs to megawatts by ratio to the 0.6 power. Therefore,

$$C_1 / C_2 = \left(\mathrm{MWe}_1 / \mathrm{MWe}_2\right)^{0.6}$$

With the known cost and size of one plant, the cost of another size plant can be estimated. Obviously, the results are not precise, but they provide an order-of-magnitude estimate from known data.

5.6.5 Dismantling technology differences

Decommissioning technology has been evolving over the last ten years or so, using the advances in computer technology to provide more accurate control of remote cutting processes such as reactor vessel and segmentation of internals. In addition, new technologies have been adopted from other industries such as the high-pressure abrasive water jet cutting system for segmentation of the reactor vessel and internals.

Even more routine activities such as small diameter pipe and conduit cutting have advanced from oxyacetylene cutting to oxy-gasoline (petrol) cutting, oxy-propane cutting, and hydraulic shears. Hydraulic shears have a two-pronged effect (no pun intended) of shorter cutting times, and minimal spread of contamination. While the speed differences may be small on a single pipe basis, the large number of pipes to be cut makes these advances significant in the overall project.

5.6.6 Stakeholder requirements

Local and regional stakeholders have had a major influence as to how decommissioning activities are to be performed. In some cases, stakeholders have been able to over-ride federal regulations on material and facility release criteria to more restrictive levels, thereby adding materially to the overall cost. Stakeholders have also influenced the decommissioning strategy adopted, requiring expedited dismantling rather than a safe storage period of many years.

5.6.7 Waste material transport/disposal/storage differences

The waste material transport has also been an evolving process, transitioning from strictly truck transport to barge, rail, and truck transport. Where barge shipping facilities are available (a local port and barge docking facilities), long-distance transports are generally more cost effective than rail or truck. Where barge facilities are not available, rail transport is more cost effective than truck transport.

Similarly, LLRW disposal has been changing in the United States. Under the National Low Level Waste Policy Act of 1986, states were to form regional compacts to provide disposal capacity for the nation's commercial LLRW. As many as 16 compacts and disposal sites were envisioned, but they never materialized. Instead, only four commercial LLRW disposal sites are operational:

Atlantic Compact—Barnwell, SC (Energy Solutions, Inc.)
Northwest Compact—Hanford, WA (US Ecology, Inc.)
Andrews, TX (Waste Control Specialists, Inc.)—an independent waste disposal facility
Independent Facility—Clive, UT (Energy Solutions, Inc.)

Individual states have signed agreements with these disposal sites for their NPP wastes.

5.6.8 *Inflation factors between estimates*

Obviously inflation plays a role in the reported costs of decommissioning. Estimates are generally reported on an "overnight-dollar" basis, assuming all the work would be performed instantaneously. No inflation is included in these estimates. Inflation is generally accounted for in the provisions for the DTF because the collection period covers 40–60 years until decommissioning occurs. Accordingly, the year of the estimate comes into play when comparing estimates of two different NPP estimates or ACs.

5.6.9 *On-Site Storage of Used Nuclear Fuel*

The issue of on-site storage of spent nuclear fuel (SNF) arises when a country does not have a designated facility for disposal, or long-term central storage installation. The costs to remove spent fuel from the NPP fuel storage pool to on-site dry storage facilities (independent spent fuel storage installations—ISFSIs) is a significant additional expense prior to completing dismantling of a NPP. Some countries' regulations do not recognize this cost as a decommissioning cost, but rather as an operating cost. The US NRC's Minimum Funding Amount excludes spent fuel storage in its calculations, but recognized licensees may include it in their DTFs as long as it is identified separately.

For countries with fuel reprocessing plants, the cost accounting for this expense may be treated differently. It may come under a government-funded obligation or be treated as an operating expense.

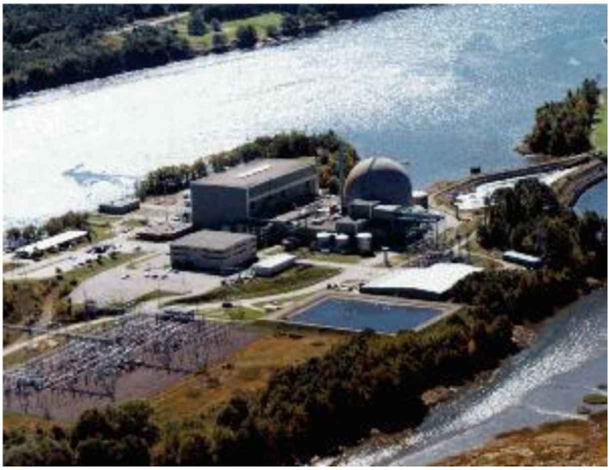
5.7 Selected examples of real costs versus estimated costs

Most of the NPP DCEs in the United States were prepared by TLG Services, Inc. (a subsidiary of Entergy Nuclear, Inc.), and several were prepared by Energy Solutions, Inc. These estimates were prepared primarily for establishing DTFs, but some were also used to plan the actual dismantling work. In this section, selected examples of United States estimated versus ACs will be provided and some of the major reasons for the differences between estimated and ACs will be discussed.

In addition, two other reports were prepared comparing estimated costs to ACs in both the United States and international sectors. The first was a draft report entitled, "Assessment of the Adequacy of the 10 CFR 50.75(c) Minimum Decommissioning Fund Formula," by Pacific Northwest Laboratory in 2011 for the US NRC [10]. The final report was never published. This report provided a detailed analysis of the estimated and actual decommissioning costs of several US NPPs. The reader is encouraged to review this report.

The second report was published by the OECD/NEA entitled, "Costs of Decommissioning Nuclear Power Plants," OECD 2016, NEA 7201 [11]. This report reviewed several international NPP estimated and AC estimates and how this information can influence funding decommissioning projects. Again, the reader is encouraged to review this report.

5.7.1 Maine Yankee



The Maine Yankee NPP was a 920-MWe PWR Combustion Engineering design. It began operations in 1972 and was shut down in 1997. The original estimate was $508 million in 1997 dollars as shown in Table 5.3, which included an ISFSI for fuel storage until 2023 [12]. The DOC, Stone & Webster Corporation, was terminated from their fixed price contract for financial problems in other parts of its business. Maine Yankee (and Entergy Nuclear) took over the management contract on a time and materials basis. Other than the relatively minor problems they encountered during vessel internals segmentation, other problems arose with the local stakeholders (local residents). Maine Yankee had proposed to rubblize (crush) slightly contaminated concrete (and mix it with some clean concrete) to dispose of it on-site as fill in below-grade voids. The stakeholders insisted that no potentially radioactive concrete would remain on site as fill, and the State of Maine's environmental agency further required that such concrete was "special waste" that would potentially leach out calcium and other trace materials and contaminate the land. Maine Yankee decided to totally remove all radioactive or potentially radioactive concrete and ship it to Envirocare in Utah. All clean demolished concrete was removed and shipped to an industrial landfill in New York State. The State of Maine further intervened by mandating the site license termination release criteria be reduced from the US NRC value of 25 mRem per year to 10 mRem per year. This further complicated the project, but surprisingly not to a great extent. The final AC of the project was reported in several documents as $495 million (EPRI—after deducting for contractor credits) [13].

The steam generators and pressurizer were internally grouted to fix contamination during transport, and they were shipped intact for disposal at Barnwell, SC. Maine Yankee decided to use the high-pressure abrasive grit water jet cutting system for segmenting the reactor vessel internals, and the utility insisted the contractor construct a full-size mockup and fully demonstrate the cutting technology and grit collection and filtration system. Even with these additional precautions, the grit filtration was a problem, but it was quickly corrected by the contractor. The reactor vessel internals

Table 5.3 Maine Yankee decommissioning cost estimate ($ in 1997)

	Cost item	Costs (×$1000)	Ratio (%)
1	Staff personnel cost	133,216	26.21
2	LLW disposal cost	83,379	16.41
3	Dismantling and demolition cost	60,214	11.85
4	ISFSI installation and permit	52,249	10.28
5	Asset tax	31,031	6.11
6	Waste treatment/ recycle	22,473	4.42
7	Security service	15,930	3.13
8	Non-rad building demolition	15,078	2.97
9	Transportation cost	12,881	2.53
10	Decontamination	12,024	2.37
11	License termination survey	10,580	2.08
12	Soil remediation	9063	1.78
13	Energy cost	8944	1.76
14	Insurance	7420	1.46
15	NRC charge on ISFSI	6936	1.36
16	Packaging	6339	1.25
17	NRC charge on EP	6309	1.24
18	Overhead cost	5904	1.16
19	Others	8253	1.62
	Total	508,223	100.00

were cut into large sections and placed into specially designed liners, which in turn were placed into dry storage casks. The casks were placed on the ISFSI until the government repository for high-activity waste is available. The reactor vessel was placed into a specially designed shipping container and stored on site for almost one year until the water level of the Savannah River rose sufficiently after a drought to handle barge transport. The vessel was transported by barge to Barnwell, SC, for disposal. Maine Yankee's vessel internal segmentation experience built upon previous experience and resulted in an overall shorter segmentation period. The two-fold effect of a shorter cutting duration and an overall shortening of the project duration resulted in reduced overall decommissioning costs. The overrun of the estimated cost was a result of changes in the scope of the project that were not reflected or revised in the original estimate.

The lessons learned at Maine Yankee were to involve the stakeholders early and get agreement on critical issues involving the site and surrounding areas that will remain after the decommissioning is complete. This applies to the disposition of concrete, soils, and material shipped to a local industrial landfill for disposal. It also applies to gaining acceptance of local stakeholders of the site release criteria to be met for termination of the reactor license. Another lesson is to ensure specialty contractors such as vessel cutting companies fully demonstrate their cutting technology on full-scale mockups, including the methods for capturing and disposing of all cutting swarf and other secondary wastes.

5.7.2 Yankee Rowe

The Yankee Rowe NPP was a 167-MWe PWR early Westinghouse design. It began operation in 1961 and was shut down in 1990. The first cost estimate was made in 1994 at $370 million, including a three year safe storage period, and $45 million for an ISFSI for spent fuel storage until 2018 as shown in Table 5.4. A second estimate was prepared in 1999 at $407 million, primarily to account for "unanticipated" polychlorinated biphenyls (PCBs) and barium found in the paint used on the containment

Table 5.4 Yankee Rowe decommissioning cost estimate ($ in 1994)

Period	Activity	Costs (×$1000)	Period
1	Safe storage preparation	8716	95.01.01–95.06.30
2A	Safe storage (in SFP)	80,755	95.01.07–99.12.31
2B	Safe storage (in ISFSI)	24,310	00.01.01–02.06.30
3	Dismantling/ preparation	19,616	02.07.01–03.06.30
4	Dismantling/ decontamination	132,608	03.07.01–04.12.31
5	license termination	5956	05.01.01–05.06.30
6	Site remediation	24,256	05.07.01–06.06.30
7	ISFSI operation	44,954	06.07.01–18.12.31
Decommissioning cost (NRC)		341,171	
CRP cost (CRP-1)		28,900	
Total decommissioning cost		370,071	

Table 5.5 Actual and estimated costs to decommission the Yankee Rowe Nuclear Power Plant ($ in 2003)

Activity	Costs (×$1000)
Actual decontamination and dismantling 1992–2002 (unescalated dollars)	347.9
Estimate to complete—2003–2022—decontamination and dismantlement	97.1
Estimate to complete—2003–2022—radioactive waste disposal	20.0
Estimate for SNF long-term storage on site until 2022[a]	129.2
Estimate for site restoration[a]	0.3
Estimate for final site survey	4.0
Contingency	37.9
Total actual and estimated costs	636.4

[a] Included but not part of US NRC required decommissioning activities.

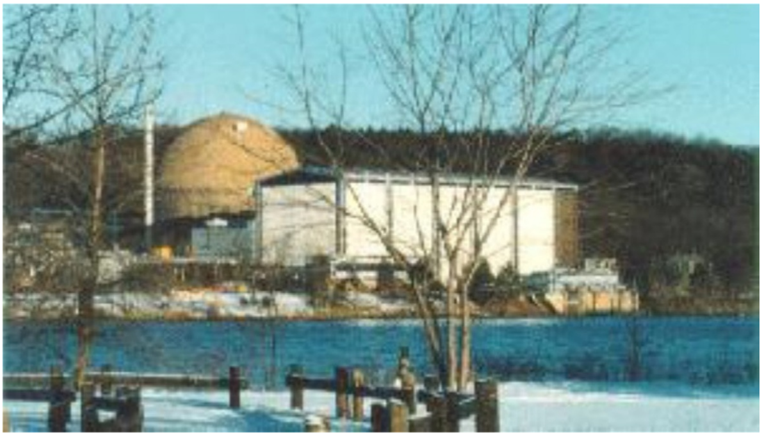
vessel and on interior surfaces. Work crews also discovered contaminated soil, some of which occurred as they removed the PCB paint from the exterior of the containment building that washed into the soil. The ISFSI costs escalated as well during this period when cask designers and manufacturers incurred additional regulatory requirements, driving up their costs. The final AC reported was between $636.4 million in 2003, as shown in Table 5.5 [14], and $750 million [15].

The steam generators and pressurizer were internally grouted to fix contamination during transport, and they were shipped intact for disposal at Barnwell, SC. Yankee Rowe elected to segment the reactor vessel internals using a plasma arc torch. The segments were cut into sizes to fit a special spent fuel canister (approximately 10 in. square), to fit into the liner of a spent fuel shipping/storage cask. This involved a great deal more underwater cutting, with additional problems of recutting to break away slag that formed on the back face of the cut. In some cases the cut section did not fit into the liner, and it had to be re-inserted into a cutting fixture for additional cuts. The swarf from the plasma arc thermal cutting was not properly controlled, and it was dispersed throughout the service pool where cutting was being performed. This caused an unexpected dose to the cutting crew, and visiting NRC regulatory personnel. Lead shielding had to be added to the cutting bridge above the pool to protect the workers. The reactor vessel was placed into a specially designed shipping container and transported by truck, rail, and barge to Barnwell, SC, for disposal.

The lesson here, as at other sites, is to perform a thorough site characterization of radiological and hazardous materials before starting decommissioning. Definitive characterization is the cornerstone of good estimating and rigorous project contracting and management.

If the costs of on-site storage of SNF are not included, the costs for decommissioning would be $507.2 million.

5.7.3 Connecticut Yankee (Haddam Neck)



The CY NPP (also called Haddam Neck) was a 582-MWe PWR Westinghouse design. It began operation in 1968 and was shut down in 1996. The cost reported in the post shutdown decommissioning activities report (PSDAR) as shown in Table 5.6 was $426,727,000 in 1996 dollars [16], which included wet storage of spent fuel, and it later was changed to dry storage. Connecticut Yankee (CY) contracted the work to a large contractor for a fixed-price contract (estimated at $200–$300 million) to manage the project as the DOC. The contractor discovered on-site soil contamination and claimed it was out of scope and therefore should be covered by a change order to their work. CY disagreed and a legal dispute ensued. CY terminated the contract and took over management of the project on a time and materials basis. CY discovered there were 93,000 cu ft of slightly contaminated soil that had been stored on site, but it was low enough to be sent to a local landfill. Local newspapers and politicians made big news over this issue, causing CY much embarrassment. CY also discovered there had been a concrete block building that was demolished on site some years earlier.

Table 5.6 Connecticut Yankee decommissioning cost estimate ($ in 1996)

Activity	Costs (×$1000)	Ratio (%)
Staff personnel cost	69,726	39.8
LLW disposal cost	61,265	14.4
Demolition	35,147	8.2
Decontamination	3638	0.9
Packaging	1845	0.4
Transportation	7644	1.8
Others	94,920	22.2
Contingency	52,542	12.3
Total	426,727	100.0

The operators at the time separated the clean blocks from the contaminated ones, and they invited the local residents to take the clean blocks. The next morning all the blocks were gone—both clean and contaminated. CY spent more than $18 million retrieving the blocks (some had been used for building foundations, barbecues, etc.) and restoring the structures from which they were taken. CY then addressed the soil contamination problem that the contractor had uncovered. It had penetrated below the soil and into the groundwater. Again, the local politicians took major issue with this problem. Ultimately, the project costs reported in the literature varied from about $850 million [15] to $931 million [17] including on-site spent fuel storage to date.

The steam generators and pressurizer were internally grouted to fix contamination during transport, and they were shipped intact for disposal at Barnwell, SC. CY decided to use high-pressure abrasive grit water jet cutting system to cut the reactor vessel internals. Poor filtration of the cutting pool water resulted in extensive contamination of the service pool, with grit mixed with greater-than-Class C swarf. It took almost two years with the help of a specially designed remote-controlled arm to clean up the service pool. The internals were segmented into larger pieces to fit in specially designed liners that were placed in dry storage casks and are stored on site on the ISFSI. The reactor vessel was placed into a specially designed shipping container and transported by barge to Barnwell, SC, for disposal. The lesson here is to perform a comprehensive site characterization program before embarking on any work.

Table 5.7 shows cost data from the EPRI report on Connecticut Yankee decommissioning [17] of the ACs spent between 1997 and 2002; it also shows the estimated future costs to decommission the Connecticut Yankee nuclear plant through 2023, at which time it was assumed SNF would be shipped to a federal repository. These costs are based on a 2003 estimate to complete.

If the costs of on-site storage of SNF are not included, the costs for decommissioning would be $613 million. The reported completed cost of actual decommissioning varies depending on who reported the costs. Some authors included spent fuel storage costs, while others did not. Some included site restoration, and others did not. The earlier noted costs of $850 to $931 million are probably in the correct range for the

Table 5.7 Actual and estimated costs to decommission the Connecticut Yankee Nuclear Power Plant ($ in 2003)

Activity	Costs (×$1000)
Actual decontamination and dismantling 1997–2002 (unescalated dollars)	327
Estimate to Complete—2003–2023—decontamination and dismantlement	106
Estimate to Complete—2003–2023—radioactive waste disposal	65
Estimate for SNF long term storage on site until 2023[a]	318
Estimate for site restoration[a]	100
Estimate for final site survey	15
Total actual and estimated costs	931

[a] Included but not part of US NRC required decommissioning activities.

2003 completion date. This is typical of the frustration in attempting to correlate ACs to estimated costs, and it is the primary reason the OECD/NEA and IAEA published the ISDC document.

5.7.4 Big Rock Point

Big Rock Point was a 67-MWe General Electric Co. BWR located in northern Michigan. It was owned by Consumers Energy. It began operation in 1962 and shut down on Aug. 29, 1997, just three years before the end of its operating license, because improvements to meet future regulatory requirements were not considered cost effective given the small size of the plant. The ISFSI stores the plant's spent fuel until it can be shipped to a national repository. The license termination was received from the US NRC in the first quarter of 2007. The estimated cost of decommissioning was \$439.4 million [18] as shown in Table 5.8. The final AC for decommissioning was \$472.8 million [19].

The lessons learned from Big Rock Point were related to the delays caused by late delivery of the dry spent fuel storage casks due to licensing problems of the cask

Table 5.8 **Big Rock Point decommissioning cost estimate (\$ in 2003)**

Activity	Costs (×\$1000)
NRC radiological costs	333.9
Site restoration	30.3
Spent nuclear fuel costs	73.6
Post-9/11 incremental security costs	1.6
Total costs	439.4

vendor. The cask vendor had to resubmit its NRC licensing application to meet more restrictive cask design requirements. This caused an unexpected delay in emptying the spent fuel storage pool and subsequent dismantling work in the pool area. The lesson is to ensure the cask venders have a licensable design.

5.7.5 Rancho Seco

The Rancho Seco NPP was a 913-MWe PWR Babcock & Wilcox design. The plant operated from 1975 through 1989. The owner, Sacramento Municipal Utility District (SMUD), decided to self-perform the decommissioning using annual funding provided by SMUD. This funding approach greatly extended the duration of the project. The original TLG Services, Inc., estimate was $281 million in 1991 dollars, based on an assumed LLRW disposal cost of $450 per cu ft. The state of California had planned on constructing a low-level radioactive waste disposal facility but the costs of construction and operation escalated rapidly and by 1999 were up to $1000 per cu ft, and its opening was abandoned. SMUD provided an initial funding limit of $15 million per year and later increased it to $27 million per year. The operating staff managed the project and used major subcontractors to perform the work. The history of TLG and SMUD staff cost estimates is shown in Table 5.9, as SMUD adjusted the estimate according to the amount of work completed and the remaining work to be accomplished. This is the preferred way of tracking decommissioning progress.

The total decommissioning costs were estimated to be $504.3 million in 2010 as shown in Table 5.9 [20]. This was later revised in 2012 to be $517.1 million [21].

As an example of the breakdown of these cost estimates, Table 5.10 shows the cost elements for Rancho Seco in 2005 dollars [22].

SMUD determined the steam generators and pressurizer were too large and heavy for the local roads, so they were segmented using a combination of a diamond wire saw and oxylance thermal cutting methods, and they were packaged for transport to Envirocare in Clive, Utah. SMUD also decided to cut the reactor vessel head using oxylances (a thermal cutting lance using pure oxygen to burn magnesium and iron

Table 5.9 History of Rancho Seco decommissioning costs

Year of cost study	Estimated cost (×$1000)	Decommissioning organization
1991	281	TLG
1993	365	TLG
1995	441	TLG
1997	452	TLG
1998	459	SMUD
1999	458	TLG
2000	495	TLG
2001	504	SMUD WITH TLG
2002	519	SMUD WITH TLG
2003	524.3	SMUD WITH TLG
2004	529.7	SMUD WITH TLG
2005	534.1	SMUD WITH TLG
2006	538.1	SMUD
2007	522.9	SMUD
2008	498.2	SMUD
2009	503.9	SMUD
2010	504.3	SMUD
2012	517.1	SMUD

Table 5.10 Rancho Seco decommissioning cost and estimate to complete ($ in 2005)

Remaining activity (2006 and beyond)	Costs (×$1000) (2006 and on)	Rate (%)
Decontamination	2663	1.6
Large component and R/B concrete demolition	28,429	17.4
Transportation	2768	1.7
Waste disposal	7126	4.4
Radioactivity characterization/remediation	14,961	9.2
Final status survey	13,434	8.2
Staff personnel cost	52,730	32.3
Material and equipment cost	3278	2.0
Insurance	1156	0.7
Other nondistributed cost	12,811	7.9
Contract and material additional charge (contract and material surcharge)	823	0.5
Survey on waste storage	1994	1.2
Disposal cost for class B, C, and GTCC	20,552	12.6
Total	163,088	100
AC until end of 2005	371,097	
Total	534,185	

powders in a tube to achieve high temperatures). Unfortunately, the vessel head was left in position over the reactor vessel, allowing the dross (cutting debris) to fall into the reactor vessel, thereby further contaminating the interior of the vessel. With respect to the reactor vessel internals, SMUD decided, in light of the problems encountered with high pressure abrasive grit water jet cutting at other sites, to use mechanical cutting of the internals. Cutting the internals by mechanical methods proved much more difficult than envisioned. It took more than one year to make the cuts, and cutting equipment had to be redesigned in the middle of the project to complete the job.

The reactor vessel had to be segmented as well, because the load carrying capacity of the local roads could not handle the full weight of the vessel and its transport container. The utility decided to use high pressure abrasive water jet cutting, a process not formerly used on reactor vessels elsewhere. The process used much more grit than originally planned, and it required an extensive cleanup activity at completion. The AC of decommissioning was \$518.3 million [23]. The license has been terminated by the US NRC. The remaining work includes demolition of the containment building and other structures on site. These costs are technically not US NRC decommissioning costs but nevertheless are considered as such at other sites.

The lesson learned from Rancho Seco is to carefully select specialty contractors for the critical activities such as reactor vessel and internals segmentation. Require the contractor to demonstrate at its own facility on a full-scale mockup the proposed cutting technology prior to awarding the contract.

5.7.6 Additional reading

The reader is encouraged to review two estimated-versus-AC reports for further information:

“Costs of Decommissioning Nuclear Power Plants,” OECD 2016, NEA 7201, Paris, FR [10]
“Decommissioning Experiences and Lessons Learned: Decommissioning Cost.” EPRI, Palo Alto, CA: 2011. 1023025 [24]

5.8 Conclusions

There has been a large number of NPPs decommissioned in the United States and internationally. Many lessons have been learned to advance the technology of planning, licensing, dismantling, waste management, and site restoration. The practice of cost estimation has improved greatly over the years, first by the introduction of computer technology which permitted the handling of large data bases quickly, which also permitted evaluation of multiple scenarios to allow the selection of meaningful strategies and scenarios. The science of cost estimation has evolved from an art to a defined practice, with cost estimating standards established by the industry and accepted guidance provided by personnel with hands-on experience. Courses and workshops in cost estimation are available to guide less experienced estimators in providing well-defined and reliable cost estimates.

The practice of reporting ACs of decommissioning represents the next challenge to the industry. Past experience has been disappointing to say the least, with owner-licensees and contractors unwilling to share AC information on the basis of claims of proprietary data. Even when cost estimates are made available, in-the-field tracking of those costs has been poorly followed. Either the accounting programs used by the owner-licensees are incapable of tracking that level of detail needed to account for the labor, materials, equipment, waste management, etc., or they are unwilling to spend the time and money to properly collect such information.

There are ways around this dilemma of proprietary cost information: by reporting, for example, worker hours for each activity. These can be more readily converted to monetary values in any currency for purposes of comparison of ACs to estimated costs. But here too, there has to be some incentive for owner-licensees to expend the effort to collect and then report such data. So far, this has not happened.

For owner-licensees anticipating near-time decommissioning projects, and wanting to compare their estimates to ACs the (sometimes called ‘benchmarking’), the problem is one of matching up the BoE for the plant to be decommissioned to the BoE of a recently completed project of similar size, complexity, and scope of work. Even finding the BoE of these competed projects is a challenge for the estimator because not all this information is available in the public domain. Some of this BoE information is available from the original estimators, while other such information had to be learned from technical papers presented at conferences and workshops or by talking directly to project personnel who actually worked in the field on the project. The task remains to attempt to adjust the cost estimates to the ACs, accounting for NPP differences, scope of work differences, inflation differences, and potential unreported cost overruns by contractors working on a fixed-price basis.

5.8.1 Cost estimating improvements build confidence in the nuclear industry

The need for improved cost estimates has focused attention on the better definition of the work scope and the BoE. Concurrently, improved computer programs provide greater detail to be included in the estimates so that on-the-job tracking can be improved. All of these serve to build confidence in the estimate and the ability of companies to predict future costs. The nuclear industry needs this type of improvement and credibility building to survive against competing energy sources.

5.8.2 Assure safe decommissioning years into the future

The ability to predict with accuracy the costs of decommissioning and to provide sufficient funding for the safety of workers and the public now and in the future is the basic objective of decommissioning funding. Having the proper, comprehensive computing tools is part of that process. The tools the industry learned about QA for the operation of NPPs also apply to the preparation of DCEs. The same rigorous policies and practices must be applied to the preparation of DCEs as would be applied to any operational or manufacturing process for NPPs. Every DCE must be properly documented so that it can be used with confidence in the detailed planning and implementation in the field.

5.8.3 Sets an example for other industries to follow (mining, oil, coal, gas, and manufacturing)

The DCE processes and practices developed for the nuclear industry can set an example for other industries such as mining, oil, coal, gas, and manufacturing. These industries virtually ignored the end-of-life scenario as to what to do with the facilities when the natural resources were depleted, or when the market no longer supported the manufacturing plant. The nuclear industry is virtually the only industry that has properly planned for ultimate retirement of its facilities and the proper site restoration and potential reuse of the land.

5.8.4 The path forward

The next steps for decommissioning cost estimation involve developing a process and obtaining support for reporting actual decommissioning costs in a retrievable and useful manner. This information can be valuable in benchmarking DCEs for future funding and implementation needs. The difficulties discussed earlier in obtaining this information from utility-licensees and contractors can be overcome by including contractual requirements for contractor reporting of man-hours to perform each and every task (or group of tasks), as well the crew composition of superintendents, foremen, craftsmen, laborers, and HP techs. It may also require utility-licensees to add tracking personnel to the management staff to perform on-the-job reporting of progress and productivity. The OECD/NEA announced its intent at the Madrid, Spain Conference in May 2016 [25] to start a new initiative to develop the methodology and practices for benchmarking current and future decommissioning projects. This is a major step in the right direction.

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New and unexpected stakeholders in decommissioning projects

M. Laraia
Independent consultant, Rome, Italy

6.1 Introduction

Woodhead's preceding book about nuclear decommissioning [1] included a chapter entirely devoted to stakeholders [2], which mostly addressed the local communities. However, many things have changed over recent years, which were hardly reflected in the abovementioned reference and justify updating and further elaboration.

Historically the notion of stakeholders has changed, reflecting the growing importance of populations that were previously excluded from the decision-making in industrial projects. Initially, interactions within a nuclear activity (for our purposes, decommissioning) were essentially limited to "statutory" stakeholders, typically the responsible organization (also interchangeably called the decommissioning organization, the operating organization, or the licensee in this chapter), the nuclear regulator, and the government as the entity ultimately responsible for whatever happens in a given country (and more often than not, the provider of decommissioning funds). The public was typically ignored in the decision-making. This approach reflected a mentality whereby responsibilities were legally codified and happily left to legally responsible parties. Interference from the world outside the responsible parties was unacceptable.

Time has shown that the picture of statutory parties evolved in line with the complications of modern technologies. For example, regulatory bodies other than the nuclear regulators became involved (e.g., labor or industrial regulators) and different governmental bodies were involved (all departments caring for the interior, industry, labor, finances, environment, agriculture, welfare, tourism, foreign affairs, etc.).

Over time, a number of nonstatutory stakeholders emerged, beginning with the local communities who felt directly impacted by the industrial project taking place in their neighborhood. These categories did not feel fully protected by national bodies (which inevitably care for general, rather than local, interests and worries) and became increasingly vocal in asserting their rights. In response to local claims, the operating organizations, the regulators, and the government in all their articulations opened communication channels with the local communities: initially communications tended to be one-way (basically, just a transfer of minimum information from the organization in charge), but it was soon realized that feedback from the locals was desirable for the success of the project. Conversely, and soon enough it was learned

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that the lack of the operating organization's interest in public involvement could readily impact the project negatively. It was also realized that public communities are not monolithic, but different, often conflicting, views between individuals and subcategories of the public come to light. This makes harmonization of different goals more difficult. Information on the concerns of local stakeholders in nuclear decommissioning projects and guidance on their best involvement is given in Ref. [2]. A recent development in this area is a trend toward establishing associations of communities active in national and international fora including, among others, the Nuclear Legacy Advisory Forum (NuLeAF, UK), *Associación de Municipios en Áreas con Centrales Nucleares* (AMAC, Spain), Energy Communities Alliance (ECA, United States), and Group of European Municipalities with Nuclear Facilities (GMF, Europe). These communities are willing to share experiences with communities newly impacted by facility shutdowns and decommissioning. However, local communities are not only those in the vicinity of the nuclear facility under decommissioning, but also those near the waste disposal site where decommissioning wastes are shipped. The former see radioactive contamination leave, while the latter see it arrive. See Ref. [3] for a conflictual case.

More recently, it has come to the attention of the decommissioning community that a range of new, at times unexpected, stakeholders show up in the course of decommissioning projects and exert pressure on statutory members of the projects. The purpose of this chapter is not to assign priorities or define whether and when these not-so-obvious stakeholders are or are not expected to appear; rather the chapter has the less ambitious objective of identifying them in an arbitrary order. By and large, it is felt that disregarding the concerns of *any* stakeholder (i.e., *anyone* who claims to be a stakeholder) can be worrisome regarding a decommissioning project.

It should also be noted that some stakeholders may outlive the decommissioning project because the impacts of the project are felt longer than expected. Concerns can be raised after the completion of the project (e.g., residual radioactive contamination, occupational diseases, or undue, unaccounted expenses): in some circumstances the decommissioning organization may have disappeared and any remaining issues will then reverberate on the regulators or the government. It has been mentioned for a developing country [4] that after demobilization some contractors tend to remain and not return to their homes because they either cannot afford it or they do not expect to find work in their hometowns. Increasing crime rates have been reported, consequently.

The following description of stakeholders has not been written in a specific sequence because it reflects neither priority nor number of associated events. National nuclear agencies, operating organizations, regulators, and waste owners are encouraged to maintain good relations with all external stakeholders in order to prove their societal responsibilities and to prevent significant hindrances to the smooth proceedings of the decommissioning project. The information below is an update of Refs. [5] and [6]. A general overview of stakeholder involvement in nuclear decommissioning is given by Ref. [7]. A review mostly focused on local communities has been published by the OECD/NEA [8].

For the practical purposes of this chapter, the stakeholders have been separated in two categories: Section 6.2 of this chapter deals with particular segments of the statutory regime and specific interests within the local communities, and Section 6.3 addresses more distant interests. The reader should note that a sharp distinction between these two broad categories is impossible: for example, the media (Section 6.2.1) have been included in Section 6.2 as bearers of local interests, but newspapers and TV channels of national circulation incorporate and report diverse interests of the kind given in Section 6.3.

6.2 Visible (statutory and local) interests

6.2.1 Media

Like it or not, quite often the public has more confidence in the media than in the decommissioning organization, the regulators, or other statutory "experts." While some in the media may have biased opinions (e.g., an antinuclear sentiment) with which they try to imbue the public, others purely reverberate the information they are given by the decommissioning organization or alternative experts. The continual flow of news coming out of a decommissioning project is also essential in communicating with these particular stakeholders and through them with the general public. It is imperative for the decommissioning team produces trustworthy and skilled communicators ready to answer questions from the media at short notice and to follow up as needed. It can be important to distinguish between the national media and the local media, which have different scopes and goals. Fig. 6.1 shows a group of journalists visiting the Vandellos decommissioning project in Spain.

Fig. 6.1 Vandellos NPP decommissioning project: journalists looking at waste containers. Courtesy of IAEA, Planning, Managing and Organizing the Decommissioning of Nuclear Facilities: Lessons Learned, IAEA TECDOC No. 1394.

6.2.2 Visitors

Visitors are generally attracted by decommissioning sites due to the wide coverage of those activities by the media. They take their impressions home and may contribute to the good image of such projects. In addition, tourists give substantial support to the local economy, even in the long-term if they are attracted by the landscape or other remaining features, and they may be instrumental in promoting the revitalization of decommissioned sites. To create the conditions for such developments, it is imperative that decommissioning projects be equipped with information centers including observation points. Additionally visitors should be given a chance to understand what is occurring at the site.

The Hanford decommissioning/environmental remediation project can be considered a typical project that has raised considerable interest among the general public. The public-local, regional, and national—has also influenced Hanford's environmental remediation. They are not only curious about the formerly secret site, but also anxious to understand the cleanup process, its priorities, its pace and sequence, the risk profile of various actions, the type of technologies being applied, and the funding. Those living in communities around the site and the two million people downriver want credible assurance that the Columbia River, regional drinking water, and other resources are safe. They have also a vested interest in ensuring their tax money is being spent wisely.

Today Hanford offers one of the most vigorous and extensive public tours and visitor programs in the DOE complex. By overwhelming popular demand, the tours also take the visitors to the nation's national historic landmark, Hanford's B reactor [9].

It may sound weird, but tours of the accident-hit Fukushima site by visitors are becoming popular. By September 2015, that is, four-and-a-half years after the nuclear accident, some 16,000 visitors had toured the site. Soon after the accident visitors were mostly politicians and technical experts. But later ordinary citizens became frequent visitors, partly because of the significant decrease of radiation levels at the site [10].

The current trend toward stakeholder involvement in decommissioning projects seems to be multimedia centers displaying equipment, photos, films, and increasingly, interactive sessions (for the purposes of the latter, virtual reality has possibly the greatest potential). The knowledge appealing to, and transferred to, the general public can often take the form of exhibits removed from decommissioned/remediated sites rather than paper or electronic archives. A recent example of the visitor information program is given by Dounreay, the site of the second largest decommissioning and remediation project in the United Kingdom. This includes, among others, the display of equipment removed from Dounreay facilities. The control room of the decommissioned Dounreay Fast Reactor (DFR) was donated to National Museums Scotland and the Science Museum in London for display in early 2014. The control room of the Dounreay Materials Testing Reactor, meanwhile, has been donated to a local museum in Caithness [11].

6.2.3 Miscellaneous pressure groups

One should note that there are groups interested in a number of seemingly unusual issues. Based on statements from one group, the Berkeley NPP (a Magnox reactor in the United Kingdom) decommissioning strategy was heavily affected by stakeholders' desire that the residual buildings minimize the visual impact over the long period of care and maintenance. To this end, the building height was lowered [12].

The following paragraph is extracted from Ref. [13] and refers to Bradwell NPP, UK: "Site photographs taken before the start of the project provide a good visual indication of surrounding area and help to identify potential environmental receptors in the vicinity (e.g., surface drains) and hence highlight mitigation measures that need to be implemented. Visual inspections and photographs can also provide an indication on effectiveness of mitigation measures. For example, presence of mud on roads can be an indication on insufficient wheel washing of heavy goods vehicles." Similarly, new claddings were installed outside Magnox reactor buildings to protect them from environmental agents during the long periods of safe enclosure. Design and choice of the color of cladding materials have been developed with the aim of reducing the visual impact.

6.2.4 Site planners and developers

In the near future a growing number of nuclear facilities will reach the end of their service lives and will be ready for decommissioning. Many of these will be decommissioned with the aim of either replacing them with new nuclear facilities that serve the same goal or the site may be reused for other goals (nuclear or nonnuclear). By taking account of and promoting the redevelopment scenarios of nuclear sites at an early stage in their life-cycle it is possible to include actions aimed at redevelopment as early as before or during the decommissioning project (partly), offsetting the costs of decommissioning and ensuring best use for the material, land, and scientific and technical resources available at each site. A range of involved parties will typically include the following:

- Top managers: those responsible for the definition of policy and the approval of projects.
- Property managers: many organizations have a manager in charge of "real estate." His or her duties include actions aimed at increasing the postdecommissioning value of the site.
- Technical staff: decisions by the operating organization often affect how assets (e.g., land) are redeveloped and/or converted to new uses. It is beneficial to the organization that technical staff be aware of long-range implications of policy decisions and be consulted accordingly.
- Local stakeholders: elected officials, environmentalists, and other concerned parties should be consulted at an early stage in the decommissioning process and their input requested about the postdecommissioning fate of the site and preferable options for reuse. Reuse options include a careful assessment of financial and legal issues, which in turn demand the participation of economists, lawyers, and other experts.

Interest groups in redevelopment decisions include business and trading interests, environmental and conservation organizations, adjacent properties, the unions, and others. Engaging these groups and ensuring active participation are important components of maintaining good relations.

The benefits of redevelopment to the community include such aspects as elimination of derelict areas; rejuvenation of aging industry; support to the tax base;

reduction of job losses; reuse of buildings, roads, and bridges; and preservation of unbuilt spaces for agricultural or recreational purposes. The anticipated benefits should be communicated to the stakeholders at an early stage of decommissioning. It is inevitable that some stakeholder groups will have conflicting agendas. However, having all the interest groups together, listening to all concerns, and negotiating compromises in land and facility reuse are all essential steps to ensure success of the decommissioning project.

Overall, concrete prospects of site redevelopment are expected to build trust in the decommissioning process (as well as in the operating organization and in national institution) among the local communities. Additional stakeholders that should be invited to join the meeting include the potential buyers, tenants, and any companies specializing in adaptive reuse in view of later sale. The IAEA has published two reports in the field of site redevelopment [14,15].

6.2.5 Ecologists and animalists

Nuclear power plants are favorable habitats to a range of wildlife. Buildings and nearby areas on decommissioning sites (even brownfields) offer suitable conditions to protected species including bats, birds, snakes, rodents, and amphibians. Regardless of the industrial characters of these plants, they are typically surrounded by large tracts of open land, often totaling 10–20 km^2. NPPs are also close to water courses in order to use water for cooling purposes.

The dismantling of buildings (including nuclear ones) in many countries is subject to review and consent by the land planning authorities. The licensing process will generally require an ecological evaluation. Surveys of protected species are often required in support of this evaluation: these surveys can often result in significant delays to the dismantling project. If protected species are spotted onsite, working approaches may need certain modifications including, for example, avoiding scheduling the work during the breeding season, employing less noisy dismantling methods, or by having the works monitored by a professional ecologist [16].

One case in question was reported at the Bradwell NPP decommissioning project in 2013. Peregrine falcon nestlings hatched on the roof of reactor 2 after a pair of the birds chose to make Bradwell their home. The fine gravel on the top of the reactor building provided an ideal location. Because peregrine falcons are a protected species, the plant owner, Magnox, took special care not to disturb them and Bradwell was then regularly inspected by environmental specialists. At the time the event was reported the nestlings were requiring parental care for food and warmth because they only have down feathers, which are not waterproof and are vulnerable to rainy conditions. The Magnox management had to readdress work from reactor 2 to reactor 1 to minimize delays [17].

In the Post-Shutdown Decommissioning Activities Report for the Vermont Yankee NPP, which was submitted to the US Nuclear Regulatory Commission in December 2014, it was mentioned that the main stack has an appended nesting box for peregrine falcons. The box had been placed many years before upon request of an environmental organization.

Current decommissioning plans call for the plant to lie in safe enclosure for almost 60 years prior to large-scale dismantling. At the time of dismantling the stack, the Vermont Yankee licensee will have to consult with the US Fish and Wildlife Service prior to removing the nesting box since this bird species is protected under the Migratory Bird Treaty Act [18].

6.2.6 Conflicts between regulators

Each country has a different regulatory regime. In most countries the nuclear regulator has the regulatory responsibility for verifying that the license requirements incorporated in the nuclear license (for our purposes, the decommissioning license) are fulfilled. In parallel, however, the environment agency (or a similar name) can be responsible for regulating radioactive and nonradioactive (e.g., chemical) releases from the site to the environment. In principle, these two stakeholders can at times have conflicting requirements: for example the nuclear regulator may wish to accelerate decommissioning that could momentarily heighten site releases. Another interface could be observed between the nuclear regulator and the regulator responsible for industrial work (e.g., the labor office or the like). For example, the latter can be reluctant to allow a team of mountaineers take radiological samples from the ceiling of a 20-m tall building: instead the labor inspectors may request safer sampling modes or a statistical approach minimizing the number of samples. Section 6.2.5 mentions the role of the US Fish and Wildlife Service (another statutory stakeholder) in a decommissioning project. Occasionally police/security (in many countries, a statutory entity) has statutory responsibility in decommissioning projects (e.g., to keep demonstrators at bay and prevent intrusion, thefts, and vandalism): it is not unthinkable that their role could interfere with the timing and resources of the decommissioning organization.

On a much wider sense, those responsible for security of information (groups within or without the decommissioning organization, but mostly having distinct reporting lines) are given a responsibility possibly conflicting with the concept of transparency, a desirable objective in stakeholder involvement. Former military institutions (e.g., Hanford in the United States) that have been transferred to the civilian regime for the purposes of decommissioning may more acutely experience this dilemma. A French case study is discussed in Ref. [19].

Keeping all regulators informed and each complying with their own responsibilities can be difficult with limited resources. Usually different regulators have bilateral or multilateral agreements to reconcile joint responsibilities.

6.2.7 Stakeholders within a research center

Decommissioning of a research reactor or another small facility within a research center is generally not going to attract the attention of the local communities off-site. They are used to vaguely learning about things happening “there,” and the job losses associated with the decommissioning of a small facility are not of any significance (and usually can be readily absorbed within the center itself).

However, the scientists and other staff working at nearby facilities—while normally unafraid of radiological hazards—may feel in other ways the burden of a decommissioning project situated within the same site. Increased vehicle traffic, installed barriers, congested parking lots, demolition vibration, dust emissions possibly inconveniencing their experiments, noise, and time uncertainties are all factors that can make onsite neighbors active stakeholders indeed.

6.3 Distant interests

6.3.1 The nuclear industry at large: Designers, vendors, manufacturers using materials/components removed from decommissioning sites

An often neglected opportunity from the dismantling of nuclear reactors is linked to the prompt availability of materials and components for follow up investigation. This is a twofold opportunity: one opportunity is to estimate future performance during later phases of decommissioning, for example, after a long period of safe enclosure; the other opportunity is to learn more about the behavior of such materials in new builds or in still operating reactors. The fallout of investigations are expected to increase radiological and industrial safety; to enhance the outcomes of scientific, technical, and financial efforts for the preservation and final dismantling of shutdown plants; or to improve the knowledge needed for design, construction, and operation of new plants. The stakeholders here are the designers, vendors, and manufacturers, a broad category quite distant from those closely associated with a decommissioning project. Researchers (dealt with independently in Sections 6.2.7 and 6.3.4) represent a category partly overlapping with the designers.

One area of special interest is the neutron studies of materials and components of decommissioned reactors. Success in diagnostics of neutron-irradiated constructional materials directly depends on early and accurate evaluation of radiation damage in order to establish the relationship between defect features and macroscopic functional properties of materials (tenacity, compressive strength, toughness, deformability, and other mechanical properties).

Neutron techniques allow neutron-based investigation of metallic materials (e.g., steels) and parts (e.g., welds, plates, and supports) by providing important information complementary to that obtained by such traditional methods as optical and electron microscopy or destructive methods. In detail, neutron techniques disclose information on the position and interpretation of internal stresses several mm below surface and the meaning of micro- and nano-phase parameters such as carbide size, diffusion, and volume percentage. The assessment of this data helps estimate the residual life of the component or part being investigated.

Recent projects at Jose Cabrera reactor, Spain, enlighten these developments [20]. Research directed by EPRI consisted of 70 kg of highly irradiated metals removed during the reactor decommissioning. These metal samples incorporated information from almost 40 years of neutron and gamma irradiation. A container with the samples was shipped by sea to the Studsvik laboratories in Sweden, where metallurgists are at work to deepen the mechanisms of metal irradiation damage.

Another research project at Jose Cabrera addressed concrete aging under actual scale irradiation (former studies used laboratory experiments to this end). With plant aging, information is needed to monitor deterioration of mechanical properties and estimate the residual life of irradiated materials. The Cabrera project (directed by EPRI) aims to provide more knowledge about the impacts of long-term irradiation. Accurately defining material properties and their time evolution will enable nuclear manufacturers and builders to make decisions about reactor life extension, maintenance, or the need for repair.

6.3.2 *Historians and archeologists*

In recent years, awareness has grown of the need to preserve industrial sites as cultural heritage. Because of this development, opinion groups might exert pressure on the extent of a decommissioning project and the end state. These interests may conflict with other stakeholders interested in planning for profitable redevelopment of the site.

There are a number of examples of nuclear museums planned or already established on decommissioned sites:

- Zoe, the first French research reactor
- Chinon-1 NPP, France
- HIFAR reactor, Australia
- ORNL Graphite reactor, United States (Fig. 6.2)
- B reactor at Hanford, United States (Section 6.2.2)
- EBR-1 reactor, INEEL, United States (Fig. 6.3)
- HTRE reactors, INEEL, United States
- AM reactor, Russian Federation.

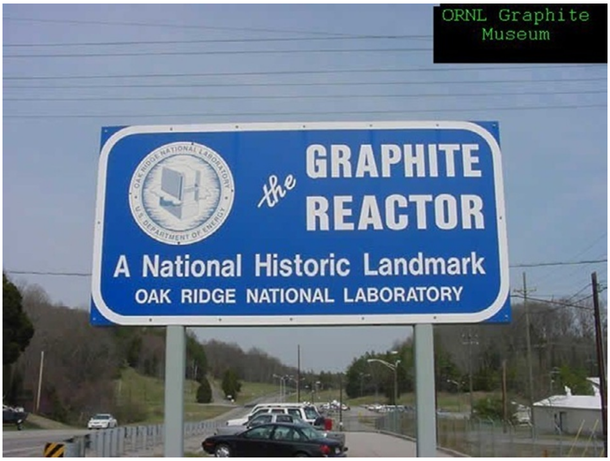

Fig. 6.2 Sign at the ORNL Graphite museum.
Courtesy of IAEA, Redevelopment and Reuse of Nuclear Facilities and Sites: Case Histories and Lessons Learned, Nuclear Energy Series No. NW-T-2.2, Fig. 29.

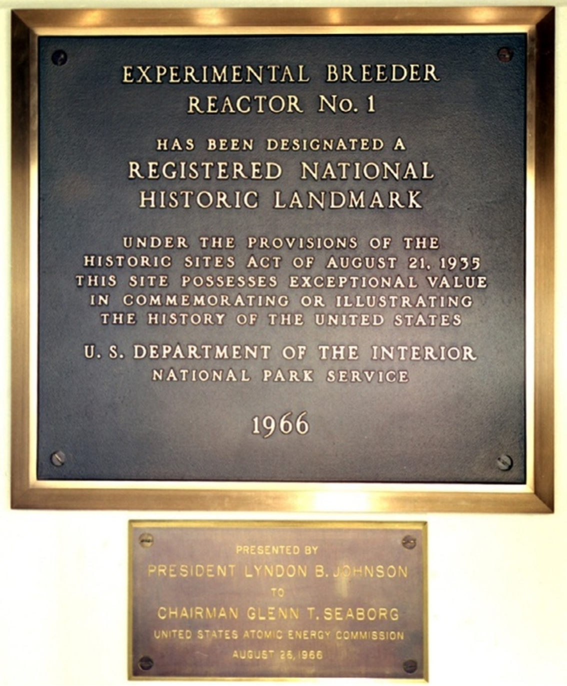

Fig. 6.3 Plaque at the EBR-1 museum, United States (Ref. [1], Fig. 18.3).

Some nuclear facilities are more suitable than others to be adapted to nuclear museums or nuclear exhibitions. This may depend on factors such as interest expected of local communities and tourists. Location and access are important factors. Conversion to a nuclear museum can also be a convenient way to release part of the site for unrestricted access while allowing radioactive decay of remaining structures. This is the case for the FR-2 research reactor, Karlsruhe Research Center, Germany.

However, environmental cleanup and historic preservation might be two incompatible objectives and trigger conflicting positions among stakeholders.

The following case exemplifies the historic and archeological interest that can be generated by an ongoing decommissioning project. Dounreay Castle is situated adjacent to the Dounreay nuclear site (under decommissioning for many years). It dates back to the 16th century and is one of the few remaining examples of a Scottish castle from that period. The castle was still inhabited in 1863, but it had become roofless and derelict by 1889, and it is now in ruins. Due to its historic importance, it has been designated by Historic Scotland as a scheduled monument.

In an early phase of Dounreay's nuclear operations, experiments with radioactive liquids were carried out from the castle courtyard. In consequence of piping leaks and spills, the courtyard became radioactively contaminated. The piping was removed, but decontamination of the area turned out to be impossible, given its archeological constraints. Contaminated drainage had also leaked through the castle gate drain, contaminating the coastal areas and beach.

In 1996, the then site owner (UKAEA) began a project to characterize and remediate the contaminated area in order to minimize the hazards of contamination migrating toward the sea, while maintaining the historic status of the castle.

With input from Historic Scotland, the site was excavated in cooperation with archeological specialists. This enabled the archeologists to establish a complete record of the archeology and history of the site.

The area was excavated to a maximum depth of 3 m, generating some 1500 t of low-level waste. This was transported to the nuclear center's waste stores, and the excavated areas were backfilled with noncontaminated soil from nearby locations, as well as with clean soil from the area excavations. The remediation project allowed open access to the castle area, and it has helped to preserve an important piece of Scottish heritage.

In 2008 the new owner (Dounreay Site Restoration Limited, DSRL) noticed a structural deterioration of the castle, which sparked concern both for staff safety and heritage aspects.

Scheduled monument status requires the owner to inform Historic Scotland of any deterioration and not to undertake any work that may further damage the castle.

Later on, DSRL received an inspection report from Historic Scotland that contained recommendations for the preservation of the castle [21].

The ruins of the castle have recently been subjected to a laser scan, which provides a complete 3-D survey of all construction details. In February 2015 a wall collapsed onto the underlying shore during heavy rain. Options to ensure safety are being explored.

A comprehensive review of broadly cultural aspects of a nuclear site is given in Ref. [22].

6.3.3 Communities of practice

A specific category of stakeholders can be named communities of practice (CoP). These are groups who regularly interact to share knowledge regarding a particular practice. They may exist throughout an organization as project teams, work groups, organizational units, and even as professional associations.

These communities include people with varying levels of experience who have interest and shared involvement in specific topics. They have a sense of common membership, trust, and readiness to acquire and share knowledge or contribute analyses and solutions with peers in the group. CoPs form spontaneously and remain active as long as the members feel that the group keeps a *raison-d'être*. CoPs usually do not need considerable administration or governance.

CoPs may exist in the "real world" or online in an organization's intranet or the open internet. A web-based CoP has the advantage that conversations among group members may be recorded and readily shared. The appearance of social networking tools has greatly improved the practicality of newly-launched CoPs.

The decommissioning-oriented D&D KM-IT is representative of CoP and CoP mechanisms. To prevent the decline and loss of decommissioning (D&D) knowledge, the US Department of Energy (DOE) and the Applied Research Center (ARC) at Florida International University (FIU) have developed D&D KM-IT to obtain and store information in an easily usable system [23]. D&D KM-IT is a web-based knowledge management information tool custom built for the decommissioning user community.

D&D KM-IT serves as a centralized repository and a common interface for all decommissioning-related activities. The main purpose of this mechanism is to upgrade efficiency, reduce the need to “re-invent the wheel,” and to circulate the available knowledge. It facilitates in acquiring, evaluating, recording, and sharing knowledge within a community of peers. Too frequently, people in one segment of the D&D community fail to solve problems quickly or optimally because the knowledge sought, while available somewhere, is not known or accessible to them. D&D KM-IT helps to foster cooperation while building upon the D&D knowledge base created by the DOE’s decommissioning community.

6.3.4 Researchers and scientists

Decommissioning is not rocket science. Like any other industrial process, decommissioning should be completed in a timely fashion and at the least cost (without compromising safety). However several decommissioning projects conducted in the 1980s and 1990s had a significant R&D component because they were aimed at the development and optimization of new techniques. For example, the European Commission through its framework programs supported the development and demonstration of innovative technologies. It should be noted that EC programs addressed firstly R&D of innovative, emerging technologies on a laboratory scale and later on focused on adaptation of these and conventional technologies to pilot projects.

At present, most experts agree that decommissioning is a mature industry and that available technology is capable to tackle all issues that can appear under normal circumstances (the decommissioning of plants damaged by severe accident is a notable exception to this statement). Continuing R&D in decommissioning can be viewed as superfluous, sort of re-inventing the wheel. However, some scientific environments still tend to view decommissioning as a research project. This is particularly true at research reactors; there the former operators’ duties for many years were to conduct research. It is often difficult for such groups to convert to the realities of an industrial project. Likewise external research teams (from universities and scientific institutes), which were active in supporting the reactor’s operation, may feel reluctant to give up their professional expectations. Researchers can represent active stakeholders in decommissioning and their priorities may potentially conflict with the selected decommissioning strategy.

By contrast, a decommissioning project granting time and financial resources to R&D is likely to enjoy the praise and active support by the scientists. This approach, though more expensive than straightforward demolition, can be selected in countries or institutions having little access to the international decommissioning market (e.g., due to costs or political constraints) and being forced to develop their own expertise. Preserving researchers' jobs is another argument for continuing decommissioning research.

Domestic expertise can anyhow be desirable in view of future projects. In this regard the role of the nuclear and nonnuclear industry in a given country should not be disregarded. The national industry may therefore appear as another stakeholder in decommissioning projects. The lessons learned from decommissioning—if gathered, processed, and used according to good plans—will reverberate on a number of other national and international programs.

There is another angle from which one should consider the role of this category. The group of researchers and academicians enjoys generally a large amount of trust from the public; They are preferentially addressed by the media because their "expert judgments" are viewed as independent from the regulator or operating organization and immune from vested interests. Developing communications with this group can be helpful to introduce scientific arguments in a public debate that could otherwise drift into vagueness or politics.

A special case is represented by patent holders. It is commonplace at decommissioning projects that newly-patented innovations are considered for onsite application. It is also quite possible that patents are generated within a given decommissioning project. This implies that interactions with individuals or companies owning the patents are inevitable, and contractual negotiations are in order. This belongs to the broader field of intellectual property. In turn, the role of legal studios in case of conflicts is not difficult to determine.

6.3.5 Medical and health professionals

This is another group frequently seen by the public as a reliable source of information. They are viewed by the public as independent experts (whereas statutory experts may be viewed as holding vested interests, and their statements can be viewed as biased). In reality, many of them often lack profound knowledge of the impacts of low-level radiation, especially given the specialist's nature of nuclear decommissioning. It is important therefore that this group be involved in the project at an early stage to enable them to understand the technical details and build confidence in the competence and goodwill of the decommissioning organization. Health professionals can effectively inform the decommissioning organization about public concerns and in this way help reduce these concerns to more realistic proportions.

6.3.6 Financial interests

In general it is always good to know where the money is coming from and what the routing/constraints are. Often there are conflicts within this area between those responsible for the stability of funding, those who hold the risk premiums, the opportunity of withdrawing monies from the decommissioning fund in advance of decommissioning, the tax treatment of accumulated funds, etc.

It goes without saying that the costs of decommissioning are going to impact the payers into the decommissioning fund or those owning shares of the decommissioning organization. These people will want to see the bills. This will certainly result in accurate cost forecasts and endeavors to reduce expenses throughout the decommissioning process. In principle it is also possible that shareholders' indications go against the strategies selected by the technical management: for example, shareholders' preference can be given to deferred dismantling, and diluted cash flows allowing the regular payment of dividends, rather than immediate dismantling, even if normalized costs showed that the latter is financially preferable in the longer run.

A relevant case in question is the Shareholder Executive, a body within the UK Government responsible for managing the government's financial interests in a range of state-owned businesses (fully or partly) in various forms [24].

The portfolio of the shareholder executive contains businesses where the shareholder executive has a shareholding mandate, although the shares themselves are owned by government departments. Its functions are either directing the ministers, supporting shareholder teams within departments, or advising department shareholder teams.

As far as nuclear decommissioning is concerned, one should note the financial supervision exerted by the Shareholder Executive on the Nuclear Decommissioning Authority (the organization dictating the overall policy of decommissioning in the UK).

Professional insurers are another category of stakeholders. It should not be unexpected that professional insurers in the decommissioning field are very cautious when it comes to underwriting this risk. But it is not necessarily the fear of nuclear accidents that makes the insurers reluctant, but the uncertainty and lack of knowledge about a nuclear facility being decommissioned [25].

We are currently seeing the first wave of nuclear decommissioning projects. For many countries this is unknown territory. Therefore there is in many countries a lack of experience and guidance. As of today it can be stated that nuclear decommissioning does not have a consolidated insurance approach beyond case-by-case makeshift solutions.

But the growth of the decommissioning market means that decommissioning is a risk that insurers will have to face, regardless of the uncertainty. Contractual insurance requirements are changing because a large number of decommissioning projects are being initiated and national legislations pose stricter requirements.

The biggest challenge insurance companies currently face to produce new insurance models is educating underwriters and brokers alike. Clients need to help fill the knowledge gap by providing comprehensive descriptions of the decommissioning process, including hazards (based on lessons learned worldwide) and the risk management measures to prevent or mitigate such risks.

Another category of stakeholders are real estate owners. These people are likely to be affected by facility's shutdown and decommissioning in many ways. Favorable impacts include the regained availability and profitability of areas formerly restrained by the presence of the nuclear facility. However, it is a fact that sites formerly used for the purposes of a nuclear facility (e.g., houses or community buildings for the operations staff) devaluate due to first, the (supposed or real) stigma inherent to residual contamination and second, the reduced number of people living in areas nearby at the completion of decommissioning. As one example, the Property Value Protection Program at Port Hope, Canada, described in Ref. [26] is an innovative strategy to counteract the risk of the individual property devaluation due to remediation and long-term management of radioactive waste that had in the past contaminated the area.

Providers of local services are also typically impacted by a decommissioning project. Typical activities impacted include food catering, healthcare, schools, shops, transport of goods and workers, etc. These services are strongly dependent on the number and type of local residents and visitors, and to what extent decommissioning will import or dismiss labor.

6.3.7 Teachers and students, universities

Long-standing, continual relationships with teachers and students and university professors in nuclear engineering or nuclear physics ensure that academic programs incorporate knowledge and lessons learned from decommissioning projects and foster the necessary growth in numbers and competence of nuclear specialists nationwide and internationally.

The Slovak University of Technology launched the European Decommissioning Academy (EDA) in 2014. The EC meeting on decommissioning held on Sep. 11, 2012 in Brussels concluded that at least 2000 new international experts for decommissioning will be needed in Europe up to the year 2025, which means about 150 each year. EDA was established in response to this need, which is especially acute in Eastern Europe. So far, EDA's training and educational activities have included lessons, practical exercises in laboratories, onsite training at NPP V-1 in Jaslovske Bohunice (Slovakia), and technical tours to other decommissioning sites in Europe [27].

The University of Manchester's Dalton Nuclear Institute is the United Kingdom's largest and most interactive academic body in nuclear R&D and high-level skills development. Established in 2005, the Institute has built a broad nuclear research capability that addresses the major issues associated with nuclear power today and in the future, especially decommissioning and radioactive waste management. It brings together a multidisciplinary team of experts from across the University to tackle nuclear energy challenges in collaboration with industry, other universities, and international partners.

The Dalton Nuclear Institute has established Dalton Cumbrian Facility, a partnership with the Nuclear Decommissioning Authority to create a center of excellence in radiation studies and decommissioning research. It maintains close links with the National Nuclear Laboratory Central Laboratory based on the Sellafield site [28].

6.3.8 International stakeholders

There are a number of international treaties that affect the course of decommissioning. To state one example among many, article 37 of the EURATOM treaty establishes requirements for European countries to report information about potential cross-boundary impacts of major industrial activities before execution: decommissioning is one of those. EURATOM experts issue opinions about the estimated impacts. A collection of expert opinions under Art. 37 for decommissioning projects is given in Ref. [29]. Other European Union requirements that may impact the decommissioning are related to “fair competition,” for example, the bidding process.

In general, international agreements to share information on decommissioning projects are managed through the aegis of international organizations. The OECD/NEA Co-operative Programme for the Exchange of Scientific and Technical Information Concerning Nuclear Installation Decommissioning Projects (CPD) celebrated its 30th anniversary in 2015. This joint committee of decommissioning project organizations began in 1985 with 10 decommissioning projects from 7 countries. Today CPD consists of 66 decommissioning projects from 25 organizations and 15 countries, and more are joining. ML check actual Nos before the book is published The CPD basically provides a confidential forum for information sharing on practical experience in nuclear decommissioning, including annual sessions of the members and semiannual meetings devoted to the in-field progress reports of individual projects [30].

Within the IAEA, a Co-ordinated Research Project (CRP) is a mechanism whereby institutions from several Member States join a partnership to share information on progress of and methods used in national projects (for our purposes, decommissioning). The achievements of the latest decommissioning-related CRP are given in Ref. [31]. Fig. 6.4 shows a detail of the Russian Annex of Ref. [31]: the information was disclosed during this CRP and published later.

Given the fact that the need for decommissioning exists on all countries, cleanup activities tend per se to take an international nature. There are three ways of international cooperation that are typically adopted. The first is through bilateral arrangements.

Fig. 6.4 Demolition of contaminated plaster.
Courtesy of IAEA, Planning, Management and Organizational Aspects of the Decommissioning of Nuclear Facilities, IAEA-TECDOC-1702, 2013, Fig. A-3.

The second is cooperation on a regional level (regions, e.g., Eastern Europe, have a number of social, economic, and scientific features in common), and the third is through international activities. The latter form of cooperation, including sharing of information, joint R&D and demonstration projects, has generated many achievements in the decommissioning domain. IAEA's CRPs are typical mechanisms to this end. International cooperation produces many benefits and is convenient for several reasons. First, sharing information and learning lessons from each other is a positive factor. This avoids reinventing the wheel. Secondly, projects originated or sponsored by international organizations are deemed more trustful and produce additional financial assistance. Thirdly, joint projects generate a network (a CoP, Section 6.3.3) and a mechanism of official and unofficial cross-reviews. This cross-review adds on technical credibility to national strategies including their progress and timing.

6.3.9 Future generations

The ethical basis for the selection of a decommissioning strategy is found in IAEA's Principles of Radioactive Waste Management [32]. Although the notion that future generations are directly viewed as stakeholders in today's projects can appear eccentric to some, the ethics pertaining to the selection of the decommissioning strategy may attribute in future a growing role to ethics-oriented stakeholders. Principles 4 and 5 below address the protection of and burden on future generations (Table 6.1), but are not prescriptive in nature. IAEA's countries are given the flexibility of assessing the implementation of these principles in current practices. More recent IAEA positions have recommended immediate dismantling as the default strategy, but the strategy selection is still subject to national rules or case-by-case justification [33].

The US DOE actively involves students of all classes in its environmental management programs. In addition to regular courses, this includes partnerships, internships, and apprenticeships. This approach can be seen as proactive to stakeholder involvement. Several examples of these activities are given in Ref. [34].

"The possibility of including the younger citizens at an early stage in the democratic decision-making process of cooperation in environmental questions gives the unique possibility of gaining commitment and support from a future group of stakeholders

Table 6.1 Radioactive waste management principles relevant to the selection of a decommissioning strategy [32]

Principle 4:	Protection of Future Generations Radioactive waste shall be managed in a way that the predicted impacts on the health of future generations do not exceed relevant levels that are acceptable today
Principle 5:	Burden of Future Generations Radioactive waste shall be managed in a way that will not impose undue burden on future generations

already today." This previous quote was from Ref. [35], a comprehensive review of the young generations' involvement in nuclear decommissioning.

6.3.10 Nonnuclear industry

A sector of the national and international industry that has a specific interest in nuclear decommissioning is the recycling industry. In most countries, reusing and recycling are the preferred options in waste management hierarchy. However, this has often been difficult for clean, exempted, and decontaminated waste arising from nuclear decommissioning.

A Spanish approach that has been conducive to the effective management of materials from decommissioning is given in Ref. [36]. In 1999, the authorities, in cooperation with the industry involved in scrap metal recovery and smelting, and the radioactive waste management agency (ENRESA), established a national regime for the radiological monitoring and control of scrap metal and the products (coils, ingots, etc.) arising from its processing. Later on, the most important trade unions and other industrial partners joined the regime. The system, known as the Protocol for Collaboration for the Radiological Surveillance of Metallic Materials, is based on a dedicated legislation and on a range of voluntary commitments taken on by the stakeholders. It is enforced through the installation of radiological monitoring equipment, radiological training, and guidance for the industry: it includes the staff involved in the metal recovery and smelting, the definition of an operational system to manage any materials identified as radioactive, and the overall improvement of Spain's radiological emergency system. As a trust-based system, the Protocol allows materials released from decommissioning projects (managed by ENRESA) to be recycled in the public sector with the agreement of all parties. A similar initiative in the United Kingdom is described in Ref. [37].

Decommissioning offers good business chances in nonnuclear-specific services, such as demolition and storage. Small and medium-sized enterprises (SMEs) could join in the large decommissioning market by offering innovative skills, such as promoting a more efficient way of servicing rather than developing high-tech, nuclear-specific tools (the latter being more appropriate to large, R&D-oriented concerns). To this end, the United Kingdom's Nuclear Decommissioning Authority has started to proactively help SMEs ameliorate their competitiveness in bidding for decommissioning [38]. A similar development in the United States is described in Ref. [39].

6.3.11 Go-in-betweens

Facilitators, mediators, and various communication specialists may play a key role in the stakeholder consultation process. These people can be seen to be independent and act as an honest broker trusted by all the stakeholders, but they are not essentially beholden to any of them. Good facilitation expertise is a skill that should be identified in good time and specific advice of the nature of the tasks including expected issues should be passed to the facilitators.

6.4 Conclusions

In the past decommissioning projects were relatively free from external constraints. They referred to small sites and were generally noncontroversial. As of today, decommissioning sites do not operate in a vacuum and are larger and more complex. As such, to integrate ALL stakeholders is becoming vital. This will be best accomplished not by advisory bodies unaware of the process, but by devising concrete partnerships between stakeholders aimed at a common objective—the radiological, industrial, and sustainable socioeconomic well-being of the local community and the other partners.

Because the nuclear regulator has in principle no mandate for local socioeconomic matters, it is up to the utility to develop stakeholder interactions. Ideally the industry could share resources, investigate and learn best practices, and develop a working scheme to transition from operation to decommissioning. This would result in less tension between the utility, the communities, and influential partners, and it would enhance the industry's prestige.

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Part Two

Execution

Lessons learned from decommissioning: What went wrong?

7

A.F. McWhirter
New Build Nuclear Consulting Ltd., West Kilbride, United Kingdom

7.1 Introduction

International experience has shown that in nuclear decommissioning, it is quite possible that things “will go wrong.” This may be due to less-than-accurate planning or failures on the part of the decommissioning contractor, but even when the greatest care has been taken, it is likely that at some stage in the decommissioning of a plant or facility, something that was not expected will occur and that the impact of this will more likely than not, be negative [1].

A characteristic of a successful decommissioning organization is not only in making adequate plans and preparations for the decommissioning activity, thereby reducing the number of unexpected events, but also in having available contingency plans to address unexpected events when they do occur to minimize their impact—in particular, to avoid injury and/or property/environmental damage.

What goes wrong is highly dependent upon the nature of the plant that is being decommissioned, its age, and its operating history. The diverse nature of the challenges associated with decommissioning plants, such as uranium mines, fuel enrichment/fabrication plants, nuclear power plants, weapons facilities, reprocessing plants, and research facilities, results in a worldwide decommissioning industry with a very diverse range of activities, each with the potential to raise unexpected problems.

This situation is further compounded by differences in safety, environmental, and other national legislations that are associated with the country where the decommissioning is to be carried out.

Despite this variability in the details of decommissioning needs, it is nonetheless possible to provide some insights into classes of problems that have occurred. As an example, the discovery that a drawing is missing or out of date represents a common difficulty regardless of whether the drawing in question is part of the design package of a nuclear power plant in the United Kingdom or a fuel fabrication plant in the United States. However, the early discovery of such a problem should lead the planner to take immediate action, for example, to reconstruct the missing record.

This chapter therefore deals with generic issues that have “gone wrong” during decommissioning, prompting decommissioning organizations to take precautions to avoid them and also to respond successfully to unexpected occurrences on those occasions when, regardless of preventive actions, they actually happen.

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In most cases, the references used in the preparation of this chapter have been derived from experiences in the United States and the United Kingdom because these two countries have many of the types of facilities that are now undergoing decommissioning worldwide and have therefore encountered, and responded to, many of the classes of unexpected events to which this chapter refers. Their generic nature enables them to be used as indicators of typical events that go wrong, regardless of the country where the decommissioning is taking place.

The examples of generic problems addressed in this chapter are given in Table 7.1 below, and these are expanded upon in Section 7.2. This table is not claimed to be complete and there will undoubtedly be other reasons for issues occurring; however, the topic areas below provide some examples of where major difficulties have arisen in practice.

Table 7.1 Classes of generic decommissioning problems

Class topic	Explanation
Management	Where failures or weakness of the management system on a site has resulted in an unexpected, negative event
Safety	Where an incident(s) involving safety has resulted in injury and/or a major negative impact on the progress of the decommissioning program
Culture	Where the organizational culture (or lack thereof) of the decommissioning organization on the site or its contractors has resulted in a negative impact on the progress of the decommissioning program
Radiological	Where an incident has resulted in the discovery of an unexpected source, potential contamination, and/or inadvertent exposure of personnel
Environmental	Where, during the implementation of the decommissioning program, a discharge(s) occurred that was greater than that planned or necessary or was outside the regulator's agreed scope for discharges
Technical	Where an assumption regarding the technical details of a plant to be decommissioned were later found to be inaccurate or the planned decommissioning method was found to be inappropriate for technical reasons, requiring a strategy change with attendant delay to the decommissioning program
Regulatory	Where the decommissioning activities were found to be unacceptable to one or more of the site regulators requiring a significant strategic change or involving detailed regulatory investigations. In this latter case, there may also be legal consequences and financial penalties. The preparedness of the regulatory body to regulate decommissioning effectively is also considered
Commercial	Where the commercial performance of a planned strategy was, in the event, found to be less successful than expected and required this to be revised
Waste management	Where, for a variety of reasons, the nature, volume or composition of a waste stream is not what was expected or where the integrity of a waste storage facility is poor, requiring urgent action to be taken

A selection of references is provided in this chapter that direct the reader to detailed advice and, in some cases, international case studies. The generic grouping used in this chapter has not been used to date to categorize problems. It is therefore likely that detailed assessment of the references' case studies will reveal more than one underlying reason for each incident; nonetheless, it is hoped that the underlying generic issue will be sufficient for the reader to consider the applicability of any given event to their own decommissioning projects.

The creation, maintenance, and use of a "lessons learned database" is recommended as a means of predicting and progressively reducing the likelihood of unexpected events and to respond effectively to these when they do occur. The database will best be generated at a corporate level of the decommissioning organization (or of a large decommissioning contractor) in order to be used for any decommissioning project the organization is entrusted with.

Before preparing such a database, it is useful to create an effective taxonomy of the lessons learned in order that the events, root causes, and remedial actions may be collected efficiently and made available to others when planning later decommissioning actions.

A suggested taxonomy for the creation and management of a lessons learned database is discussed in Section 7.3.

The list of references have been extracted from many sources, principally those available on the internet but in some cases from the decommissioning agencies involved. The format of IAEA topic reports such as the Nuclear Energy Series, the Technical Report Series, and TECDOCs provide extremely comprehensive sections on lessons learned, with many of these contained within IAEA's program on nuclear knowledge management. These documents are extremely helpful, but they also provide many references in most topic areas and should be considered for further reading [2–6].

7.2 Topics

The nature of unexpected events and problems during decommissioning will clearly be highly dependent upon the nature of the activities that had been undertaken at the decommissioning facility before its closure. In considering the things that can/did go wrong, it is important to identify root cause(s) rather than to concentrate on the details that, in a general publication of this kind, are unlikely to be relevant to all potential readers.

In reviewing a large number of reports on decommissioning problems, many root cause issues recur, and examples of these are described in this section and expanded upon by examples from actual decommissioning programs.

7.2.1 Management

There is one major issue whose failure or inadequacy tends to appear more often than any other and is therefore worthy of special mention. This is the management of the decommissioning organization. Even if the nature of the unexpected event or failure manifests itself as a safety, radiological, technical, or other type of event, (see Sections 7.2.2–7.2.6) root cause analysis very often reveals that the problem could have been avoided or its effects greatly mitigated by better, more effective management.

In some cases, the fault lies with the organization of the management, the adequacy and training of the managers themselves, and the communications within the company. In effect, the failure is that of the organization's overall management system.

In 1991, the UK Health and Safety Executive issued a guidance note—HS(G)65—originally entitled, "A Guide to Successful Health and Safety Management." It was reissued in 1997 with the revised title of "Successful Health & Safety Management" [7].

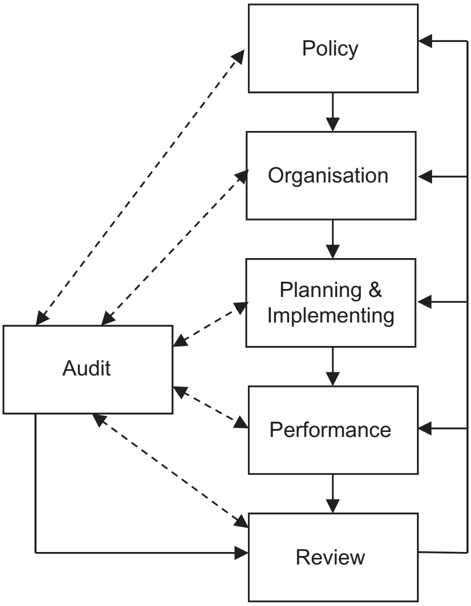
Although the document refers specifically to health and safety management, the principles it embodies can be applied to all types of management.

The management system is shown diagrammatically in the figure below.

Management must be directed to achieving compliance with a high level *policy*. This can be a safety policy, quality policy, security policy, etc.

The next step is to have an *organization* that is specifically designed to deliver this policy. This requires the correct amount of staff with relevant skills and experience to ensure that the policy is delivered.

What follows are the processes of *planning and implementing* the activities of the organization in order to ensure that the policy is delivered. In the planning and implementing elements are the detailed processes, communication routes, procedures, method statements, etc. that the organization will use to deliver the policy.



HS(G)65 management model.
© UK Health & Safety Executive.

A process of *performance measurement* is then necessary. In some cases, such as fiscal management, measurement, may be relatively easy while in others, such as safety, it can be notoriously difficult and other means of indirect measurement, such as accident rates, must be used to infer safety.

Next is a process of formal *review*. This is carried out by the staff of the organization but also with some external *audit* function (via the solid line in the diagram) to ensure that the possibility of “self-referencing,” in which inadequate account is taken of external performance of others in the field, is avoided.

Following the performance review, recommendations are made to all levels of the model as appropriate, including the top-level policy. This regular and systematic review process compares contemporary performance with external and other norms and ensures that the management system is capable of developing to meet the needs of the organization at all times and as the circumstances change.

The external audit function also audits (dotted lines in the figure) the processes to ensure that they are being implemented and that the continuous improvement, implied by the review feedback process, is working effectively.

Management failure can sometimes be traced to the lack of an integrated approach. This occurs when separate management policies and systems have been independently developed for managing, for example, safety, radiological control, waste, quality, and contracts. If these management systems are not integrated, conflicting policies such as “safety is always the main consideration,” and “the lowest fully compliant bid always wins” result in confusion at best and conflict at worst.

The International Atomic Energy Agency (IAEA) is very much aware of the pitfalls of the failure to integrate management systems and encourages the adoption of an integrated approach to the management of nuclear activities [8]. While the IAEA’s emphasis is generally associated with health and safety, quality, security etc., the inclusion in the Integrated Management System of Procurement, Finance and Programme Management helps to ensure that while safety management is not compromised, the other management arrangements are appropriately considered and that no individual management aspect is enhanced to the detriment of another.

Integrated management system

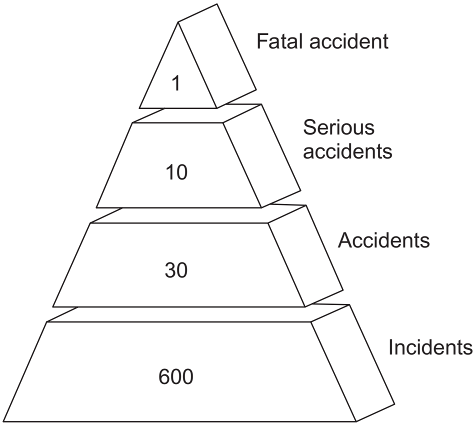
A sustainable and successful management system ensures that nuclear safety matters are not dealt with in isolation. It integrates safety, health, security, safeguards, quality, economic and environmental issues, as defined in the IAEA Safety Standards. The aim is to ensure that no separate management systems will be formed in an organization and that safety issues are of high importance in decision making.

www.iaea.org/NuclearPower/ManagementSystems

In some of the examples that follow, failure of or weaknesses in the management systems is often apparent, and it will be clear from this publication that while things can go wrong for a number of reasons, inadequate management is likely to be one of the most common. Conversely, where a safety, technical, contractual, or other problem might not have been realistically expected to happen, the existence of a competent management system that responds immediately with pre-developed contingency plans is likely to go a long way to minimizing the extent of the problem, facilitating a safe, speedy, and cost-effective recovery.

In order to prepare for a rapid recovery, it is necessary to understand the root cause of what went wrong in the first place. Having available, sufficient quantities of accurate performance data is an important way to avoid problems and to facilitate improvements when problems do occur.

Safety professionals have, for many years, used the "Bird triangle" [9] as an aid to reducing the numbers of the most serious safety incidents. The concept of the triangle is that if there are many reported minor events or "near misses" and these are adequately investigated, the likelihood of more serious events will diminish. Conversely, failing to report and investigate such near misses increases the likelihood that the more serious accidents, including ultimately fatal accidents, are very likely to occur.



The Bird safety triangle. Incidents include minor events and near misses.

The triangle itself is not a control process. Simply reporting near misses will not, in itself, decrease the likelihood of a fatal accident. It is the subsequent analysis of the root causes of the near misses and its eradication that have the effect of reducing the likelihood of the major event.

While this triangular concept was originally shown to apply to safety management, it may also be relevant to other forms of unexpected or undesired events. If, for example, it is found that there are many unexpected but minor technical deviations from a planned strategy, the analysis of these is likely to identify deficiencies in the underlying technical planning process which, when addressed, may reduce the likelihood of a more serious technical deviation. Conversely, if, when minor deviations are found necessary they are corrected informally without reporting, there is no opportunity for managers to determine underlying process failures, trends, and patterns and these may be key to avoiding a more serious technical issue.

Note. The ratios of 600:30:10:1 were developed by Frank E. Bird in 1969 based on 1931 accident data, and while these are generally accepted to be correct for safety incidents, their numerical values for other events such as technical, quality, etc. are likely to be different. What is important is the underlying idea that addressing root causes of minor events will have a beneficial effect in reducing major events.

Some consideration of this concept will quickly reveal that the use of the triangle as an indicator, coupled with competent underlying management processes, is not limited to safety, but finds applications in all areas of management. Lessons learned should include lessons at all levels of seriousness as all have the potential to impact positively on reducing more serious problems and improving overall performance.

Management systems must adapt to meet the needs of the activity being undertaken. Experience shows that the style of management that is appropriate to the routine operation of a nuclear facility may not suit safe and effective decommissioning. The management of a nuclear power plant during routine operations involves a relatively narrow envelope of activities such as startup, shutdown, refueling, maintenance, etc. Radiation and contamination levels encountered in operations are generally well-known, and shielding, provided in the design, is effective in minimizing exposures to staff. By contrast, in decommissioning, items of plant that have been located behind shielding are exposed, cut up and packaged for storage/disposal. The consistency that characterized routine operations is likely to be lost or greatly reduced in decommissioning and a different management approach must be implemented that is able quickly to develop new techniques and to respond to events that were unexpected.

The need to manage a wide range of problems, many of which could not have been foreseen, is one issue that distinguishes management of decommissioning from the management of routine operations.

This chapter deals with some of the likely issues that may confront the decommissioning team. The details will be determined by the nature of the facility, former operations, the level and nature of radioactivity of the plant, and the regulatory environment in which the decommissioning will take place. The sections below are intended to provide some examples of a generic nature and recommends that decommissioning managers should consider some of the root causes of deviations from what had been expected and capture these in a decommissioning lessons learned database, which can be referred to for future decommissioning of the site and which can be shared with decommissioning agencies in other sites and countries.

No specific example of events that went wrong in the area of management is included. Instead, the reader is invited to consider all of the topic examples below and to identify not only the topic lesson learned, but also what improved management arrangements might have been prepared and deployed to either predict or avoid the event or to minimize its consequences when it occurred.

7.2.2 Safety

Many unforeseen events in decommissioning can result in safety being compromised or even in injury to individuals. Similarly, a safety-related event, incident, or accident can have a major impact on the decommissioning program.

Safety-related incidents can occur even though there has been no departure from the planned decommissioning method. In such cases, the root cause is usually associated with insufficient planning or the discovery of a situation that was not expected and for which no contingency plan had been prepared. This situation is considered in Section 7.2.6, as a technical problem that was not anticipated.

This current section concentrates on the situation where a safety event has occurred as a result of a departure from the planned decommissioning method, while a planned decommissioning activity was being undertaken.

Typically, safety-related events in decommissioning occur as industrial injuries, that is, not specific to the nuclear content of the work. Worldwide, the nuclear industry prides itself in its approach to nuclear safety; during routine operations, serious nuclear-specific injuries such as overexposures, contamination, and ingestion are generally rare.

In decommissioning, there may be procedures that on first sight could be considered to be routine but actually require new techniques and technologies to be designed and built for a specific purpose. Because of the specific nature of the design and use, the equipment or technique may only be used once. In these circumstances, the opportunities for “on the job” training, a successful method used in routine operations by which experienced staff mentor newcomers, is frequently impossible. Instead, those who develop the technique or operate the problem-specific equipment have to do so progressively, in effect, learning as they go. In the United Kingdom, the regulatory license conditions [10] require that all activities that can affect safety are only carried out by suitably qualified and experienced persons (the SQEP concept). In decommissioning, despite much training on new equipment, inactive mock-ups, etc., until decommissioning operations begin on the real, active plant, the level of experience of the staff is likely to be lower than is generally the case for routine operations, requiring greater attention to detail and close management supervision to avoid accidents. In this respect, routine decommissioning operations resemble more closely those associated with the commissioning phase of a new plant where experience is obtained as the commissioning operations proceed.

In most cases, following a safety event, there will be some impact on the decommissioning program and the associated costs because enquiries are set up to identify the root cause. Additional safety checks may be applied to subsequent activities in an effort to minimize, so far as reasonably practicable, the likelihood of a repeat event and the extent of the investigation, and revised plans will often be reflective of the seriousness of the safety event itself.

In serious safety-related incidents, there can be legal intervention which, in addition to delaying the decommissioning program, can result in prosecution and fines for the decommissioning organization. The extent of these legal interventions will be determined by the seriousness of the incident.

Safety incidents such as those described above may appear to be difficult to predict because they may not be systematic but result from a temporary lack of attention on the part of those who implement or supervise the work and often fall into the category of industrial injury, to separate them from those of a nuclear or radiological nature. It therefore follows that proper attention to safety management at the project planning stage can avoid many safety events and/or may minimize the seriousness of those that do occur.

As an extreme example, during the decommissioning of the Windscale Pile Chimney No. 2 in the United Kingdom, an operative fell 95 m to his death.

In 1957, a fire occurred in Pile 1, one of two plutonium production reactors at Windscale in the United Kingdom, (now part of the Sellafield site); afterward, both piles were permanently shut down. Some activities such as defueling were carried out at the time. However significant decommissioning was not started until the 1990s.

The Windscale Pile chimneys—Pile 2 Chimney is on the left.
Reproduced with the permission of Sellafield Ltd.

The chimney of Pile 1 was severely contaminated during the fire and it was decided that the decommissioning technique would be developed at Pile 2, where the radiation and contamination levels were much lower.

A temporary working platform was designed and installed inside the chimney and an acceptable method statement had been prepared. Workers from a local contractor were operating inside the chimney from this working platform, and as a further precaution they were provided with fall arresting harnesses.

Despite the apparent adequacy of the method proposed, an operator, finding difficulty in carrying out the removal of a heavy metal beam, deviated from the method that had been devised. This deviation was not approved nor observed by anyone.

During the work, the metal girder that was being removed fell while at the same time causing the operative's harness to be cut by a metal bracket. The weight of the girder pulled him off his working platform, and with his harness cut, he fell 95 m to his death.

The immediate cause of this event was the deviation from the prescribed, safe working method: however, it was established by the regulators (UK's Health and Safety Executive) that had there been adequate monitoring of the work, the departure from the safe working method would have been identified and an acceptably safe alternative method would have been developed, which would have avoided the accident.

This tragic example shows that when nonroutine operations such as the decommissioning and dismantling of a radioactive chimney are being planned and undertaken, assumptions about the level of understanding of the process on the part of those who undertake them cannot be assumed and additional management and supervision must be applied. Nonroutine operations of this kind are typical of nuclear decommissioning.

A fundamental lesson to be learned from this tragic accident is that no matter how detailed and rigorous method statements and risk assessments are, if those who perform the work are not trained on the procedure, their understanding of the process is not confirmed, and their compliance with it is not monitored, accidents are likely to occur. Safety management, like all forms of management, needs to be a control process in which feedback, in the form of monitoring compliance with safety working practices, is used to maintain the safe progress of the work. In the absence of such monitoring, there is no control feedback and the safety performance cannot be guaranteed.

Many decommissioning activities are carried out by semi-skilled individuals working in confined or congested spaces with uncomfortable personal protective equipment (PPE). They must be trained not to deviate from the method prescribed and if that method is found to be unsafe, uncomfortable, or difficult, they should stop the work immediately, report the difficulty and allow those who prepared the method to revise it, taking into account the initial problem but also addressing all of the safety considerations.

Developing alternative, safe method statements is necessary in cases like this; however, it is not sufficient. It is important to ensure that those carrying out the work are following the correct interpretation of the method statement, and often the best way to ensure this is for the work to be observed and supervised by the person(s) who prepared it to avoid corruption in understanding. The use of mockups or 3-D simulations may often help in this regard.

The most significant outcome of this accident was the death of the operative. However, the site operator, British Nuclear Fuels Ltd. (BNFL) was fined £150,000 and ordered to pay £50,000 in costs. The employer of the operative was additionally fined £100,000 and ordered to pay £25,000 in costs.

These fines came after a 5-year investigation that caused an equivalent delay to the decommissioning program and additional decommissioning costs. The damage to the image of the decommissioning organization (and possibly to the nuclear industry as a whole) is hard to quantify but is likely to be significant.

Following the incident, BNFL carried out a detailed review of the events and published the findings in an internal note. The following lessons learned have been extracted from this note:

1. A formal process should be prepared to ensure that both the client and the contractor have sufficient demolition capabilities in their organizations (*Note: demolition as opposed to decommissioning).*

2. To facilitate Step 1 above, demolition-related competences should be defined, enabling competent persons to be involved in all stages of a demolition safety case.
3. The demolition safety case should include dismantling plans, detailed work methods, and demolition procedures.
4. Risks should be identified and responsibilities for risk should be allocated to whichever party is best able to minimize them.
5. Care should be taken in preparing pre-tender health and safety plans to identify conditions and factors that could affect safety and requirements for increased management scrutiny, levels of supervision, and other controls at the point of work.
6. Methods of work and project management plans must be sufficiently detailed to avoid misinterpretation, deviation from identified practices, and allow for an adequate safety assessment.
7. Training records of contract personnel must be routinely reviewed against agreed training requirements prior to the start of work.
8. Clients should adopt formal standards and expectations for conducting work and challenging deviations communicated to contract personnel.
9. Pre-work briefings should be carried out and these should adequately involve and engage contract personnel at the point of work to reinforce the behaviors required and expose any difficulties.
10. Post-work feedback arrangements should be in place to identify emerging difficulties with the job and enable improvements to work practices to be identified and implemented.
11. Changes to working practices should be reviewed and assessed to ensure the following:
    - consistency in scope with existing approved documents prior to their introduction
    - control of the total risk due to both radiological and conventional safety hazards is not compromised
    - consistency with safety case principles
    - changes are within contractor’s core skills.
12. Local inspections must be carried out and these must place adequate emphasis on working arrangements actually being followed at the work place in order to identify introduction or emergence of inappropriate or undesirable behaviors and work practices.
13. Local audits should be conducted, and these should provide assurance that the construction contract is performed in accordance with procedures.

7.2.3 Culture

There may be many reasons for unexpected, negative events in decommissioning, and management has been particularly identified as a major theme. However, as was seen in Section 7.2.2 above, even if a safe and effective process is designed, if it is not followed, there is a high potential for bad events to occur.

Reasons for deviation from the expected behavior of staff may be difficult to determine; however, cultural issues may make the management of a decommissioning program more difficult than it might otherwise be. Simply stated, if the culture of the decommissioning staff is not consistent with accepting management decisions and instructions, it is unlikely that the managers will be effective and the potential for difficulties may increase greatly.

There are many good reasons for using the staff of a facility who were involved in its operation, to carry out some or all of the decommissioning. However, if an in-house-based strategy is adopted, adequate provision must be made for the task of changing the staff culture because in many cases, the culture that had developed over many years of operation may not be consistent with the needs of safe and efficient decommissioning.

Regardless of the country involved, many of the plants and facilities that are currently subject to decommissioning were formerly government owned and operated over an extensive period of time. Such plants were often located in remote locations for security purposes and because the nature of the work was hazardous and the science not fully understood.

As a result, the original operations staff tended, in many cases, to have a "civil service" culture which, while it served the original operational objectives, was not consistent with 21st century decommissioning and completion-oriented management. Furthermore, the remoteness of the locations resulted in an insular approach in which little cognizance was taken of management techniques being employed elsewhere in the country and the world. When operations ceased and the plant moved into decommissioning, this insularity reduced the awareness of how modern program and safety management practices were deployed in the decommissioning programs elsewhere.

Staff who have been involved in the operation of the plant for a long time sometimes resist, often very strongly, the decision to cease operations and move to decommissioning. This brings with it problems and challenges to the authority of the facility's management.

Two examples where this happened are described below—at the Dounreay plant in the United Kingdom and at Kozloduy in Bulgaria. Both suffered from cultural problems but for very different reasons.

Following the application by Bulgaria to join the European Union, its accession was granted subject to the condition that Kozloduy Nuclear Power Plant, Units 1–4 would be shut down and decommissioned. At the time of the accession, money had been provided from the Phare and TACIS programs to upgrade the plants following the accident at Chernobyl. Large sums had been spent reinforcing the safety of these units, and the instruction to shut them down and decommission them was met with incredulity.

Time and effort were spent by many in the country, at the senior government level, at the senior level within the utility, and at the operational level within the site to resist the legal requirement to shut the plants down and begin decommissioning.

The situation was compounded by the fact that the numbers of staff working at the site was very large compared with other equivalent power plants and they could see that their livelihoods were likely to be lost because the plants were decommissioned.

Many years were spent changing the viewpoints of the staff and government officials while, at the same time, spending time and money in considering from a socioeconomic position what could be done to provide sustainable employment in the area following the closure of the plants.

Progress with the decommissioning of Kozloduy Units 1–4 has been much slower than would have been possible had a completely new decommissioning team been employed; however, as a counter to that, much of the detailed knowledge of the plant would have been lost.

A conclusion of this is that while the technical aspects of a plant are important to its effective decommissioning, major delays can be introduced if the culture of the staff who are currently employed there and/or who will be employed there in the future is not fully considered.

Conversely, some staff who, while not used to working in such a high efficiency environment, may relish the prospect of doing so and may seek to accelerate the decommissioning process to demonstrate the extent to which their capabilities have advanced. Unfortunately, in some cases, this acceleration in performance is not accompanied by the required improvements in training and expertise and can lead to shortcuts being taken, which, in the absence of adequate controls and management supervision, can result in major problems.

One such example was the incident in 2005 in the intermediate-level waste (ILW) cementation plant at the Dounreay site in the United Kingdom. This plant was designed to mix intermediate-level liquid waste raffinate from former reprocessing operations with a powdered cement mixture in stainless steel drums. The drummed solidified waste was then stored pending the availability of a national strategy for the long-term disposition of this material.

The Dounreay Cementation Plant.
Reproduced with the permission of DSRL and NDA.

The cementation process takes place in a new building, constructed specifically for this purpose. The liquid waste is stored in shielded tanks, mainly underground, in an adjacent building. The waste materials have heterogeneous chemistries reflecting the different types of fuel that had been reprocessed in the past at what was formerly a research facility.

Before cementation occurs, a measured quantity of liquid waste is transferred to a mixing vessel in the cementation plant and a quantity of sodium hydroxide is added to neutralize the otherwise acidic liquid and make it suitable for cementation.

About three months before the incident, due to the chemistry of a particular batch of waste, significant quantities of particulate were generated when the sodium hydroxide was added, and this had a tendency to block some of the pipework. It was, however, found that by reducing the settling time in the mixing vessel (set at 10 min by the plant Programmable Logic Controller (PLC) based control system) to 2 min,

Senior operator's station.
Reproduced with the permission of DSRL and NDA.

the problem could avoided. A manual override was therefore provided to enable the discharge valves from the mixing vessel to be opened manually after 2 min, and a temporary operating instruction was issued, specifying when and how the override could be applied. This override was applied via the human-machine interface (HMI) of the plant control system and was only to be applied by the senior operator under password control, from his operation station that was located on the roof of the mixing cell.

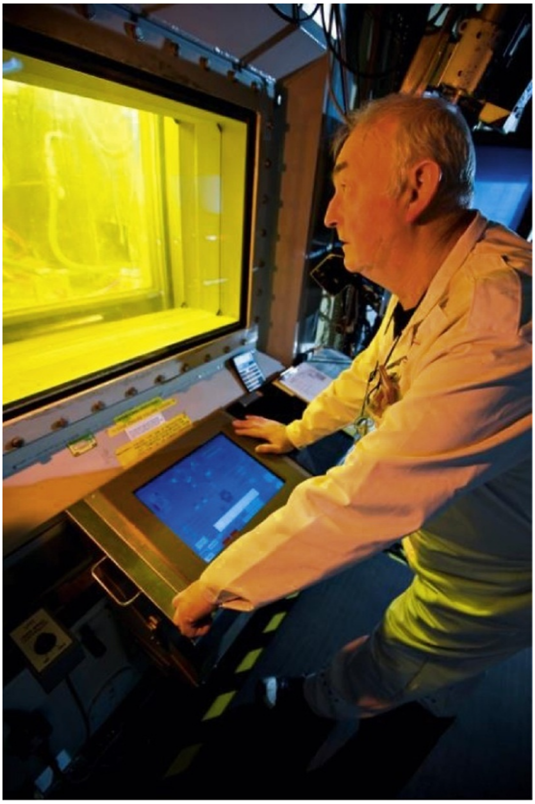
Routine operations were carried out by the other operators from HMI terminals at the cell windows from where, unlike the senior operator, they could see operations taking place through the shielded windows.

Four weeks before the incident, an intermittent fault with a sensor developed and this inhibited the operation of one of the valves that transferred the neutralized liquid waste to the cementation cell. This valve was one of two that were subject to the override procedure referred to above.

In normal operation, an empty 200 L drum containing an in-built mixing paddle is loaded through a gamma gate to the first stage of the process. Here, the drum lid is removed by a lid removal rig, the drum is raised to form a seal with the liquid waste vessel, and a measured quantity of liquid waste is loaded into the drum. When this is complete, a stirrer motor engages with the paddle and over a period of time, a measured quantity of cement power is added while the mixture is stirred.

As the mixture solidifies, the torque on the paddle increases and eventually, a shear pin breaks enabling the stirring motor to be disengaged, and the solidified waste, along with the "lost" paddle, remains in the drum.

The lid is replaced and the cemented waste is allowed to cure during a 24-h period as the cemented drum moves along a conveyor in a shielded area of the plant. Finally, after a number of other operations and checks, it is moved to the ILW store. Details of these operations are not included here because the incident in question occurred before these later operations were able to take place.



Cell wall operators' HMI station.
Reproduced with the permission of DSRL and NDA.

Progress with the immobilization of the waste had been under way for some years, with almost 2000 drums being successfully cemented and transferred to the ILW storage. The performance of the plant and the team was improving, reducing plant down time and accelerating the cementation program, which when complete would have immobilized almost all of the stored liquid ILW on the site, removing one of its biggest hazards.

On Sep. 26, 2005, a routine operation was planned. A clean, empty drum was correctly loaded into the cell; however, it failed to rise correctly to seal with the fill nozzle in the cell. An alarm to this effect was raised on the HMI but no action was taken. This failure also inhibited the removal of the lid by the lid removal unit and another alarm was raised but again not acted upon. Previous failures of this kind were not uncommon and had resulted in a revised procedure by which the lid removal unit was moved manually using a remotely operated manipulator. In this case, the same procedure was used; however, the operator failed to notice that on this occasion the lid was not attached to the removal unit.

Manual manipulator operations at the cell face.
Reproduced with the permission of DSRL and NDA.

Because the drum and lid configurations were incorrect, the PLC correctly inhibited the admission of the liquid waste to the drum. However, the override was used to open the inhibited valves in order to overcome this. As a result, liquid waste was poured onto the drum, which still had its lid in position, and from there to the floor and sump of the cell.

High sump level alarms were initiated. However, despite this, the cement powder was also admitted to the cell, spilling onto the top of the drum and also onto the cell floor and sump.

It was soon realized that there was a major problem and operations staff looked at the cell through the shielded windows and saw that the drum was out of position and its lid still in place.

The mixture of cement and liquid waste on the top of the drum and on the cell floor hardened, leaving a great deal of contamination on the drum and also on the cell floor. Naturally, no provision to recover from this situation had been made in the design and the resulting hardened waste material was very difficult to remove remotely.

An immediate investigation took place which identified a number of immediate and underlying issues. A table from the investigation report is reproduced below.

The incident investigation report (L3/05/09) [11] describes the detailed actions of the operations staff. It is clear that they ignored many indications that the conditions in the cell were very different to those associated with normal operations, yet they either ignored these indications or, where necessary, used overrides intended for a different purpose in order to keep operations going when they should, with hindsight, have ceased.

In Table 7.2 above, the item relating to "*improper motivation*" is likely to have been very significant. While there is a conclusion that "there was no evidence of undue pressure to meet production targets," it was clear that while management was not pressing for improved performance, the staff themselves were pressing to improve throughput, and that in the circumstances, one could have expected senior management to question the procedures and ensure that shortcuts were not being made. In fact, the report of the investigation makes this clear and the basic causes listed in Table 7.3 above include

Table 7.2 **Immediate causes**

Cause	Comment
Using defective equipment	The operators operated the plant with a number of faulty inhibits and workarounds to faulty equipment
Failure to identify hazard/risk	The implications of overriding the PLC to operate V115 and V296 (the liquid waste admission valves) were not fully understood
Failure to check/monitor	There were several opportunities to identify that the drum had not been raised or the lid removed No checks were carried out prior to using the override key
Failure to communicate/ co-ordinate	The communications between shifts and from shifts to day was inadequate
Defective tools, equipment, or material	There were a number of faulty inhibits and failures of equipment
Inadequate warning system	The alarms were acknowledged at the cell roof rather than the cell face. Some alarms are not repeated on the HMI
Inadequate instructions/ procedures	DCP/TOI/05 (The temporary instruction for the use of the overrides) did not bound the scope of operations for which it was to be used, or the timescales for review

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Table 7.3 **Basic causes**

Cause	Comment
Lack of knowledge	Poor initial training of supervisors led to poor understanding of potential effects of using override
Improper motivation	There was an improper attempt to save time or effort in using workarounds rather than repairing the faulty equipment
Inadequate leadership/ supervision	A wide range of issues including the following: • Improper delegation of the override • Inadequate training • Inadequate identification of loss (the term used in the DNV ISRS system) • Lack of supervisory knowledge • Inadequate management oversight
Inadequate engineering	A wide range of issues including the following: • Inadequate assessment of loss • Inadequate design • Inadequate controls • Inadequate evaluation of changes
Inadequate maintenance	Maintenance needs were not passed on to day staff or to maintenance teams
Inadequate work standards	A wide range of issues including the following: • Lack of coordination with design teams • Inadequate procedures • Inadequate monitoring of use of procedures • Inadequate monitoring of compliance
Inadequate communications	Poor communications between shifts and days. Poor logs

inadequate leadership/supervision as a cause and points to inadequate management supervision as a contributory issue.

The efforts of the operations staff to accelerate performance led to the plant being shut down for over 2 years.

7.2.4 Radiological issues

One issue which regularly results in delays or other problems on a decommissioning project is the discovery that the radiological conditions differ significantly from what were expected.

Radiological events are generally believed to be able to be avoided by very detailed characterization of the plant; however, ensuring that such characterization is complete can be difficult. In fact, incidents in which decommissioning staff have received excessive doses for any reason are very few, and this is due to the care with which surveys are undertaken and to the acknowledged need for continuous monitoring and sampling during nuclear decontamination and decommissioning.

However, the fact that few workers have been radiologically overexposed does not mean that errors in surveys and associated underestimates of the radiological conditions of a plant do not occur. In fact, such errors might have potentially caused incidents if circumstances had, by chance, been slightly different. (This is a point that supports the evaluation of near-misses and minor occurrences to prevent more serious consequences in the future, as advocated by the Bird triangle in Section 7.2.1).

In an old plant where items have been discarded into hot cells with undue care and often without adequate records, there always exists the possibility that a monitoring survey will miss a radiation source that may be exposed later during the decommissioning process. In the United Kingdom, the possibility of this happening has been identified by the nuclear regulator, the Office for Nuclear Regulation (ONR), and guidance is available to decommissioning planners [12]. Guidance is also available to the ONR inspectors who review safety cases, because there is a need for vigilance in this situation, and this is available in ONR's Safety Assessment Principle RP6 [12].

Unexpected sources of radiation have often been found in hot cells where their presence may be masked by radiation from known sources. It is only when these sources are removed and it is found that the radiation levels have not fallen that the presence of the unrecorded source is discovered. While this is generally easy to detect in most cases involving ß/ɣ activity, it is much more difficult if an α-radiation source is included.

Not surprisingly, situations with latent radiation sources can exist in plants for a very long time, and in some cases, even though some decommissioning and waste management activities have been undertaken, the problem may remain undiscovered for a long time.

As an example, in 1961, the accident at the SL-1 plant occurred at Idaho Falls in the United States [13]. The reactor that was being evaluated for military applications

The SL-1 reactor at Idaho Falls.
Photo, © US DoE.

in arctic and other remote environments was being returned to service following an overhaul.

The reactor had only three control rods and these were being reconnected to their actuators by two of the three reactor operators. Accurate details of the actions leading up to the accident are not known; however, it is believed that one of the control rods was withdrawn very quickly and in the process, it injected a great deal of reactivity that caused the reactor to experience a rapid power excursion with an associated radiation release and a steam explosion. There was significant contamination in all areas of the operating floor of the reactor. Two operators died in the explosion and the third died soon afterwards.

The main reactor building was dismantled and the radioactive components were buried. In 1983, the associated auxiliary reactor area building was surveyed as a precursor to decommissioning. Contamination and radiation surveys were carried out. A plan was drawn up to cut up the various building components in a manner consistent with the radiation and contamination levels found during the categorization surveys.

However, soon after the decommissioning work began, it was found that there was unexpected contamination from building components that had been previously surveyed as clean. Further investigation revealed that following the explosion, some areas of the building had been painted with a heavy metallic paint to fix the contamination and that concrete had been poured as a capping material over some floors to fix contamination. These had been disturbed during the decommissioning/cutting processes, resulting in airborne contamination.

These findings resulted in a significant delay to the project and additional costs in order to safeguard the decommissioning staff and to dispose of waste material as radioactive waste instead of conventional building demolition debris.

A number of lessons were learned as a result of this experience at SL-1 and the following lessons were recorded by IAEA [1]:

- Records relevant to decommissioning, in particular, radiological and hazardous contaminant characterization, all require early preparation and sufficient time for extended review.
- The characterizations done before the decommissioning project, both physical and radiological, are not always a good indication of the levels of contamination that will be found at the site or the actual physical characteristics of the site.
- The process of characterizing waste streams for treatment or disposal options should be started as soon as the initial characterization data are available. Waste generator interfaces should be contacted on potential waste streams as early as possible to determine if additional sampling and analysis may be required to further characterize waste streams. This process can be very time consuming, and may lead to long delays in completing decommissioning projects [14].

While the safety significance of this example is relatively low, it could have been much worse, particularly had there been significant quantities of α-material present. Despite the low safety significance of this event, it had a major impact on the schedule of the work and a knock-on effect on the costs.

A message from this example is that despite detailed surveys, radiation sources may be expected to appear unexpectedly in many decommissioning projects—particularly decommissioning following an accident—and contingency plans on how to deal with these should they arise should form part of a well-considered decommissioning plan.

The above example took place when unexpected contamination was found in the facility being decommissioned; however, there are other possibilities for contamination events.

At Dounreay in the United Kingdom, many redundant plants are at various stages of decommissioning. Often, these plants contain ILW. In 2002, this waste was being removed from the plants in shielded transport containers and taken to building D2001. Here, it was assayed and packed into 200-liter steel drums for storage in the site's ILW store. Movement of the material inside the cell was carried out using remote master/slave manipulators with operators viewing the movements through zinc bromide radiation-shielded windows.

Building D2001 contains many shielded cells, and these have been used, historically, for a variety of purposes. One of these, Cell 3, was in the process of being cleaned out and its contents sent to the waste posting cell to be assayed, packaged, and taken to the ILW store.

The building is old, and while today's radiation shielding windows are made from lead glass, those in this part of D2001 used liquid zinc bromide as the shielding material. A zinc bromide solution is very dense and, consequently, the hydrostatic pressure inside the windows is high. Minor leaks are therefore not uncommon. Cell three's window was known to have a very slight leak; as a result, it was swabbed annually to remove the liquid that collected in front of the window.

Typical D2001 cells.
Reproduced with the permission of DSRL and NDA.

The floor inside the cell has a layer of radioactive dust, and as a result, the liquid that accumulated there was radioactive. It was swabbed on Nov. 5, 2002, using the manipulators at the window and the swabs were placed in a canister that was then placed into a posting bag to be posted out of the cell. On Nov. 11, the waste was posted out of the cell into a 5-ton transfer flask and taken to the assay station.

The following morning, the flask was moved a few meters from the assay station and parked. Later, a contractor leaving the room carried out his self check procedure and found contamination on his protective clothing. All 70 staff members working in the area were withdrawn in a well-rehearsed, controlled procedure during which it was found that two individuals had slight skin contamination and 15 others had contamination on coveralls or shoes.

An investigation very soon identified the cause of the incident. A new type of swabbing material had been used; however, the density of the zinc bromide solution was so high that the new swab material was not able to contain it. Consequently, it leaked from the container inside the flask and found a leakage path to the outside of the flask. It was estimated that this leakage was about 25 mL and dropped onto the floor. Here, it was noticed by an operator who thought that it was a drop of oil from the crane and so he swabbed it up because it represented a slipping hazard. By doing this, he spread the contamination on his shoes and others who stood in his footprints were similarly contaminated.

The level of contamination on the skin of the two people who were contaminated was extremely small and the dose received was below the level at which potential health effects can be measured.

The management procedures observed by the staff worked extremely well and no airborne contamination was detected, eliminating any discharge to the environment and no contamination passed outside the controlled area.

Despite this, the story was reported in the newspapers and a senior manager was interviewed on television. The incident itself was minor; however, the enquiry that followed, the level of media interest, and the time taken to respond to media requests was significant.

An important lesson here is that in addition to considering the possibility of radiological incidents arising as a result of decommissioning an obsolete plant, the suitability of old equipment to support the decommissioning activity must be checked because it was, in effect, the decommissioning equipment that caused this incident rather than the facility being decommissioned.

7.2.5 Environmental issues

Unexpected environmental discharges during decommissioning are relatively rare events, but if they do occur, their significance may be high.

The rarity of environmental discharge events is often due to the fact that before decommissioning begins, plant environmental management systems are upgraded to modern standards, and in a great many cases, areas to be decommissioned are enclosed in tents or larger buildings in order to contain contaminants with the new enclosures having state-of-the-art Heating Ventilation and Air Conditioning (HVAC) equipment and suitable liquid effluent monitoring and treatment systems.

When an unexpected environmental discharge takes place, it is very frequently as a result of the failure of the local environmental management systems to correctly identify waste streams and to deal with them correctly. In some cases, such as a fire in a facility which results in the spread of radiological contamination, it may be considered that the environmental discharge was not a failing of the environmental management system. However, unless the fire was caused by events that were genuinely out-with the control of the site management, the fire can be considered as a predictable and therefore avoidable initiating event that resulted in an unauthorized discharge.

Other less dramatic environmental discharges have taken place. While large-scale pollution events are likely to attract long-term international attention, some of the lesser incidents can have a disproportionate effect on costs, decommissioning timescales, and reputation.

In 2013, Sellafield Ltd. in the United Kingdom was fined £700,000 and ordered to pay £76,000 in costs following the inadvertent disposal of four bags of low-level waste to a local landfill site intended for nonradioactive, general waste.

The hazard posed by this waste was extremely low and the bags were easily retrieved without incident and correctly disposed of in the nearby national low-level waste repository. The level of the fine and the negative publicity that it attracted were considered to be excessive by Sellafield, who appealed against the court's decision. The appeal was denied on the basis that the extent of the hazard to the public was not the issue but the failure of the management system that governed the determination of the waste type and its safe, legal disposal route. The concern therefore was that if the environmental management arrangements were inadequate, waste of a higher activity could have been incorrectly disposed of with much greater consequences.

7.2.6 Technical issues

There are many examples of technical issues that led to difficulties in decommissioning. However, in many cases, these could have been predicted at least to some extent. The hallmark of an experienced decommissioning organization is not that it does not find unexpected technical difficulties, but rather, that it expects to find them and prepares its decommissioning plans accordingly. Furthermore, staff are advised that the detailed plan may well require to change and that this should not come as a surprise to them. On the contrary, they are encouraged to look for potential deviations from the intended course of action and have instructions on how to develop a revised strategy when this happens. Flexibility is key to any good decommissioning plan. The most important instruction that they are given, however, is to stop the current process immediately, bring the plant to a stable, safe condition, and then decide what alternative actions are necessary.

Only one example of a technical issue that went wrong is included here; however, many more are included in [1] and provide examples of a wide variety of technical issues that were discovered and the way in which the associated decommissioning organizations dealt with them.

The example here shows how, following an unexpected technical issue, one failure to stop and consider the best course of action when unexpected situations occurred resulted in a major change of strategy for the site and introduced many years of delays to the program and fundamental structural changes to the company, disproportionate to the severity of the initiating event itself.

On May 8, 1998, as a preparatory step for the construction of an expanded waste disposal facility, a trench was being excavated on the Dounreay site in the United Kingdom. The route for the trench had been planned. However, when excavations reached a particular location, it was found that there was a concrete slab blocking the way.

The Dounreay site in the United Kingdom.
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A decision was made to excavate below this in order to maintain progress. In fact, the concrete was encasing a high-voltage (11 kV) cable, and during the excavation process, this was disturbed and its protection system operated to disconnect the supply.

The cable was, in fact, part of the main 11 kV ring main that supplied the fuel cycle area (FCA) of the site—the area where most of the hazardous plants are located.

The consequences were further compounded by the fact that the 11 kV protection was not configured in the way the design intended, and as a result, additional protection devices operated and removed the 11 kV supply from the entire section of the ring.

The incident happened outside of normal operating hours and an electrical engineer was called to return to the site and assess the situation. He carried out some tests but due to an error in the testing method used, he concluded, incorrectly, that both circuits of the 11 kV ring had sustained short circuits and that a major fault had been introduced that would take major efforts to excavate and repair.

The loss of the electrical supply resulted in the loss of ventilation to the area of the site where many processing and laboratory buildings are located. This had occasionally occurred in the past and there had been no negative consequences such as loss of containment or contamination, so no immediate action was taken overnight.

The next day, a more detailed examination of the electrical system revealed the erroneous diagnosis and the circuit breaker that had operated incorrectly, due to the protection fault, was closed and power restored. Nonetheless, the FCA had been without power (and thus forced ventilation) for 16 h.

An inquiry was initiated but its scope was confined to the immediate issue, namely the damage to the cable, the faulty protection regime, and the failure to restore power immediately.

Soon after the incident, the safety and environmental regulators [The Nuclear Installation Inspectorate (NII)—now the Office for Nuclear Regulation (ONR)—and the Scottish Environment Protection Agency (SEPA)] issued a formal direction to the plant operator, the United Kingdom Atomic Energy Authority (UKAEA), that all operations on the site should cease other than those essential to safety.

NII and SEPA carried out a detailed safety audit of the Dounreay site and, later in 1998, published their report [15]. This criticized UKAEA as a site licensee, in a more general sense than the failure of the electrical and ventilation systems, citing these in effect as symptoms of more fundamental problems. The report made 143 recommendations for major improvements.

A major rethink of the approach to the decommissioning process was undertaken with a fundamental review of the management and staffing policies. In the event, it took three years before all of the necessary steps were taken to enable the regulators to lift the formal direction.

The three-year delay to the program added significantly to the decommissioning cost and timescale and resulted in a review of the formal conditions that are attached to all nuclear site licenses in the United Kingdom [10]. It was concluded that UKAEA had divested itself of too much of the skill and experience base that is necessary to assure safety, relying instead too much on support from contractors. To address this matter, a new license condition, LC 36, was introduced into all nuclear site licenses in the United Kingdom, requiring licensees to make and maintain an adequate supply of properly funded resources to address all activities that can affect safety and to establish adequate organizational management arrangements to ensure that the organization cannot be changed except in compliance with these arrangements.

This new license condition is reproduced below:

License condition 36—organizational capability

1. The licensee shall provide and maintain adequate financial and human resources to ensure the safe operation of the licensed site.
2. Without prejudice to the requirements of paragraph 1, the licensee shall make and implement adequate arrangements to control any change to its organizational structure or resources that may affect safety.
3. The licensee shall submit to ONR for approval such part or parts of the aforesaid arrangements as ONR may specify.
4. The licensee shall ensure that once approved no alteration or amendment is made to the approved arrangements unless ONR has approved such alteration or amendment.
5. The aforesaid arrangements shall provide for the classification of changes to the organizational structure or resources according to their safety significance. The arrangements shall include a requirement for the provision of adequate documentation to justify the safety of any proposed change and shall where appropriate provide for the submission of such documentation to ONR.
6. The licensee shall if so directed by ONR halt the change to its organizational structure or resources and the licensee shall not recommence such change without the consent of ONR.

In effect, UKAEA had divested itself of too many skilled engineers and scientists, relying instead on support from contractors. While in principle this is acceptable, it was found that there was insufficient competence on the part of the licensee to select, manage, and monitor the work of these contractors. This capability has since been referred to as being an “intelligent customer” for the purchase of safety related support services.

The incident referred to above was initiated as result of a technical issue—namely the discovery of an inadequately recorded cable, and it was later augmented in seriousness by an incorrectly implemented electrical protection system and faulty diagnosis. However, the underlying lessons learned quickly spread from the initiating technical events to cover almost every aspect of the management and operation of the site, the management and operation of other UKAEA sites in the United Kingdom, and ultimately, through LC36, to impact on the licensing and management of every nuclear site in the United Kingdom.

7.2.7 Regulatory issues

Experience in decommissioning has shown, from time to time, that while there have been problems for the site operators and decommissioning contractors, the move from normal operations to decommissioning also needs careful attention by the regulators.

Just as there is a need for new types of activity, new risks and management challenges for the site operator and contractors, regulating decommissioning requires a different approach to that used in routine operations. While the details will vary from country to country and site to site, there is a need for the regulator to accept that new understandings, new skills, and, from time to time, new staff with different experiences are needed.

The nature of the nuclear regulatory process will also influence the extent to which regulatory approaches may need to change to address decommissioning as opposed to routine operations.

In the United States, for example, the United States Nuclear Regulatory Commission (US NRC) employs a highly prescriptive regulatory process, in which it licenses reactors and other nuclear plants, plant operators , procedures, safety related components, and activities such as construction, operations, and decommissioning.

In the United Kingdom, the regulatory system assigns responsibility for safety at all times to the licensee, applying what is referred to as a "goal-seeking" approach. The regulator requires that the licensee should "make and implement adequate arrangements" for ensuring that plants are designed, constructed, commissioned, operated, maintained, and ultimately decommissioned safely.

The United Kingdom regulator assesses (not approves) the adequacy and, if content, allows the plant to be constructed, commissioned, etc. If not, it is up to the operator to make the necessary changes and to resubmit these to the regulator for further assessment.

In these two different regulatory environments, the move from routine operations to decommissioning will be treated in different ways by the two regulators. In the US NRC system, the operator will apply for a decommissioning license. In the United Kingdom, no such application is necessary because the site license covers all activities including decommissioning. That said, the licensee must make and implement adequate arrangements to ensure that the decommissioning activities are carried out safely.

In Section 7.2.6, the incident at Dounreay involving the disturbance to a high-voltage cable was described. With the benefit of hindsight, the regulator could have been much more proactive in reviewing the adequacy of the overall management arrangements of UKAEA as licensee at the Dounreay site. Whether this may or may not have prevented the incident is difficult to say. However, in the subsequent enquiry into the incident, a number of regulatory issues were identified.

In fact, almost a year before the cable incident, in Jun. 1997, a member of the regulatory staff, having carried out reviews of safety and plant conditions in the most sensitive area of the plant, informed UKAEA as the site operator in very blunt terms that there were serious deficiencies with management, maintenance, and other aspects of operations of the site and that attention needed to be paid to address these shortcomings [16].

While the memorandum recommended that UKAEA's approach to the Dounreay site should be improved in many areas it also stated, "This is not to say that NII (the then nuclear regulator) as UKAEA's regulator, is wholly free of some of the burden of responsibility."

This memorandum was the subject of discussions in the United Kingdom Parliament and was released into the public domain in Jun. 1998, just after the cable incident occurred.

Following the 1998 incident, the regulators' final report made 143 recommendations for improvement; however, it was equally clear that changes would be needed to the regulator, its structure, and the way it regulated activities on a site where the standards of design integrity, maintenance, and environmental sensitivity were significantly lower than would be the case for a modern, nuclear power station for example.

There were some aspects of the design of old plants that obviously could not be changed because they had already been built to standards that were still developing in the 1950s. It would not be possible in many cases to modify these plants in a way that would bring them to modern standards. Consequently, a different approach was needed in which the plants were made as safe as their design allowed and that the decommissioning operations took into account the lower integrity in areas such as containment, ventilation, and shielding.

Nonetheless, some of the regulatory staff found it difficult to accept decommissioning operations being undertaken in an environment that did not meet modern standards, and this was a difficulty for both the regulator and for the licensee.

7.2.8 Commercial issues

If decommissioning of a site is being undertaken by the site owner, then the decommissioning program, its duration, cost, safety performance, etc. are all under the control of that owner. The management system used by the owner represents the means by which these parameters are measured and controlled.

An alternative approach may be to appoint a site decommissioning contractor, to manage the nuclear site and to be the site's licensee. This approach is being adopted in the United Kingdom where a single site license includes all activities from initial siting through to completion of decommissioning. A variant of this approach is used in the United States, where, for example, the US DoE gave management of the Hanford reservation site to Bechtel to carry out some of the decommissioning activities on its behalf, and similar arrangements have been carried out with Enresa in Spain.

In these cases, the control of the program, cost, and all other parameters are under the control of the decommissioning contractor.

While the responsibility for safety and performance sits with the decommissioning contractor, it is still necessary that the site owner should have a means to oversee, control, and monitor the performance of the decommissioning contractor and to take action when performance targets in any parameter (safety, environment, progress, cost, etc.) are not met.

It is therefore very important that the site owner should take great care when preparing the contract terms and conditions for the decommissioning of a nuclear site. While such care should always be taken, in the case of the decommissioning of a nuclear site, the costs run into many billions of dollars, and the duration of the contracts tends to be many years.

If inadequate attention is paid to the controls available to the site owner to influence the performance of the decommissioning contractor, then the owner has, in effect, lost control of his site. If adequate controls are included in the contract, then there is a possibility that the owner can use the built-in controls in the contract to influence the actions of the contractor and thereby improve performance in any of the areas mentioned above.

In extreme cases, it may be found necessary for the site owner to cancel the contract with the decommissioning contractor and either regain the control of the decommissioning program or to appoint a new decommissioning contractor. Such occurrences are rare; however, it is very important that the provisions are inserted in the contract to allow this to happen if necessary.

The Sellafield site in the United Kingdom.
Reproduced with the permission of Sellafield Ltd.

In the case of the management of the largest and most difficult nuclear decommissioning project in the United Kingdom the decommissioning of Sellafield—the site owner, the UK's Nuclear Decommissioning Authority (NDA), awarded in 2008 the decommissioning contract to a consortium of three large nuclear-capable companies. The contract duration was for 17 years with periodic reviews. After 5 years, in 2013, the contract was extended until the next review.

However, during this period, progress was considered to be unsatisfactory and the projected final cost of the decommissioning rose rather than fell, despite an annual expenditure of around £1.2 bn–£2 bn [17].

UK government-funded projects are regularly audited by the National Audit Office and the expenditure is subject to review by the Public Accounts Committee. Both of these bodies were highly critical of the lack of progress made and of the expenditure over the period.

In the end, the site owner, NDA, decided in Jan. 2015 to terminate the contract with the consortium from Apr. 2016, giving just over a year to effect the transition. The new arrangements involve NDA retaining responsibility for the decommissioning but using direct support to them from an industry partner, rather than handing control of the site to the contractor.

Although NDA had contracted the management of the site to the consortium, it had built in sufficient provisions in the contract to enable it to give notice of the cancelation of the contract without having to pay excessive cancelation fees and to effect the management changeover without compromising on safety.

This is an example of a situation where the project strategy, “went wrong”; however, it was able to be brought back under control as a result of adequate contractual provisions being built in at the outset.

7.2.9 Waste management issues

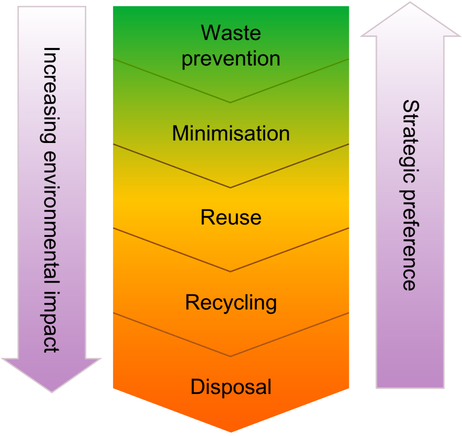
Decommissioning a nuclear facility inevitably results in the generation of waste. This may be radioactive, hazardous (such as asbestos, chemical, hydrocarbon etc.), or able to be consigned to local landfill sites or used for other purposes on the site.

Waste in general, and radioactive waste in particular, is an emotive subject and one which is not well understood by the public. In such an environment, the opportunity for things to go wrong or to be perceived to have gone wrong is significant, and the greatest care must be taken to manage waste in a fashion that is optimum and compliant with the law yet able to be perceived as acceptable to the majority of the public.

It is now widely accepted that waste management has a hierarchy as shown in the figure below.

There is limited scope for prevention in the case of decommissioning because the buildings to be decommissioned already exist and the decommissioning process reduces formerly useful plants, buildings, equipment etc. to waste to be disposed of in one way or another. Even when the best intentions are made to follow the accepted waste hierarchy, it is possible for negative, unplanned events to occur. That said, avoiding the creation of unnecessary secondary waste should always be an objective, minimizing the quantity that must be managed.

In Dec. 1999, as an example of reuse, the operators of the Dounreay Site in the United Kingdom made a gift of four redundant ISO freight containers to the local



Waste management hierarchy.

community. These had been fitted with doors, windows, and other fittings to be able to be reassembled in the local town to provide a “Santa’s Grotto” to be visited by local children during the Christmas period.

Compliant with the site’s waste transport procedures, the containers were monitored and declared to be free from radioactivity.

A local newspaper reporter discovered that the containers had, at one time in the past, been used as temporary storage for contamination zone clothing and that, in consequence, had been notionally containers of radioactive waste.

The result was a major embarrassment for the site operator and the creation of unnecessary alarm for the parents of the many local children who had, by the time of publication of the article, already visited the facility. The story, initially published in a minor local newspaper, was nevertheless taken up by many national newspapers and national television.

The grotto was dismantled and the individual components returned to the site to be disposed of in a traditional manner.

Waste minimization is a laudable objective; however, in the case of plants such as Sellafield in the United Kingdom, the volume of waste is difficult to reduce because the great majority of the waste was created several decades ago and as a result of ongoing contamination spread, the volume may actually be rising.

Sellafield was originally the site of the United Kingdom’s plutonium producing piles for the weapons programs of the late 1940s/early 1950s and the technologies reflect the uncertain nature of the science at that time. Waste management was not seen as a major priority at that time and decommissioning was probably not considered at all.

A number of storage ponds were constructed and used for the temporary storage of irradiated fuel awaiting reprocessing however, plant problems resulted in the fuel being retained in the ponds for extended periods resulting in the accumulation of large quantities of fission product contaminated sludge, as well as corroded metallic fuel bars.

First generation Magnox fuel storage pond.
Reproduced by kind permission of Sellafield Ltd.

Before reprocessing, the irradiated fuel elements, clad in Magnox (Magnesium Non Oxidizing Aluminum) were passed into a de-canning plant where the Magnox was stripped from the metallic fuel bars. This Magnox was radioactive and also contained residues of Plutonium, irradiated Uranium, and fission products.

The Magnox was stored in a series of large concrete silos which were maintained in a wet condition in order to encourage corrosion of the Magnox for size reduction purposes. Today, the material in the silos is generally a mixture of aluminum and magnesium hydroxides, with large hydrogen-filled voids.

Cut away view of Sellafield Magnox Swarf Silo.
Reproduced by kind permission of Sellafield Ltd.

The material has consolidated over the years and is difficult to remove. The presence of Hydrogen makes the removal of the material yet more problematic.

Delays to the decommissioning of some of these historic plants has sometimes resulted in leakage which has contaminated the soil, increasing the volume of waste produced and as the leak continues, the levels of activity in the soil have, in many cases, increased accordingly.

External view of Sellafield Magnox Swarf Silo.
Reproduced by kind permission of Sellafield Ltd.

The management of what are referred to as the "Legacy Ponds and Silos" at Sellafield represent the greatest challenge for decommissioning and waste management in the UK's nuclear decommissioning program. There may be a view that as we descend the Waste Hierarchy, things become easier—that it is more laudable but more difficult to minimize, reuse, recycle, etc. and that ultimately disposal is easy. As the Sellafield legacy ponds and silos demonstrate, disposal, the only option available, is by no means an easy option.

7.3 Lessons learned databases and their users

It has been stated many times in this chapter that the nature of the problems encountered in nuclear decommissioning will be highly dependent upon the nature of the site being decommissioned. Similarly, the lessons learned will have varying degrees of applicability to individual decommissioning programs, reflecting the specifics of the site and its operating history.

However, a mistake that has been made in the past in the specification of lessons learned databases is to go directly to the specific issue, such as to "conduct a full search of the site for buried cables and services before any excavation is planned."

This is an important, if somewhat self-evident lesson that has been learned at many decommissioning sites. If such detail is incorporated into a lessons learned database, it quickly becomes too big to manage and equally difficult to use.

Instead, therefore, of specifying the database in terms of the physical issues involved, it may be better to begin by considering who the recipient of the database will be and to construct it using a taxonomy that makes it more immediately relevant to those who might use it.

As an example, if the first heading of a database entry is entitled, "Intended Recipient," it will make it easier and less intimidating for the user to look at only those issues that are likely to be important to him.

Typical users of a lessons learned database may include the following:

1. Government;
2. Funding agency;
3. Site owner;
4. Site licensee;
5. Regulators;
6. Contractors.

Partitioning the database in this manner may, for example, help ensure that those issues that are relevant to a national government official are collated together and not distributed alongside recommendations on the isolation of electrical power from a building which will, of course, be of interest to the licensee and contractors.

In considering the above high-level list, it is clear that the possibility for overlaps will exist. In the United Kingdom, the funding agency is the government although the responsibility for the disbursement of funds has been allocated to the NDA. There will therefore be an overlap in the relevance of lessons learned between the NDA and government.

In a site such as Kozloduy NPP in Bulgaria, the funding agency is not the national government but the national government has a great interest in the decommissioning program and will be interested in different lessons learned.

Likewise, the site owner may also be the licensee. This was the case in the United Kingdom until 2004, when the NDA was formed. In fact, a possible lesson learned from the United Kingdom experience is that a separate agency, which is appointed as the site owner and has agreed upon funding, can have a beneficial effect on the efficiency of the decommissioning program.

The types of lessons that can be learned for government and the site owners are of less interest, in general, to the site contractors who will employ staff to cut cables, decontaminate walls, and demolish buildings; therefore, removing these lessons from their section of the database will help to make what remains more directly relevant.

Recalling that the detail of the lessons learned database will reflect the nature of the former activity at the site, it is important to keep the lessons as general as possible and provide guidance that will lead the reader to move from the high-level concept down to the more detailed lessons that may eventually be relevant.

This provides the possibility to encourage the reader to consider whole areas which might not otherwise have been considered. For example, the incident at Dounreay where the cable was disturbed (see Section 7.2.6) might result in simple lessons such as better surveying before excavating and stopping when conditions are found that are different to those expected. However, a more important lesson here for the site owner or licensee could be that simple mistakes in a routine activity can have a disproportionate effect on the long-term decommissioning strategy so that the suitability of the existing staff, management system, and the plant to be subjected to decommissioning should be confirmed before the activity commences.

The simple lesson referred to above, to the effect that excavating without adequate survey, will be of interest in sites where excavations are expected. However, the higher level lesson learned that the staff, management and plant need to be suitable for decommissioning, will be relevant to all decommissioning programs, regardless of the former use of the site.

It follows that to be of maximum use to decommissioning planners, the taxonomy used in a lessons learned database must itself be general, and in the paragraphs that follow, some of the possible lessons learned from decommissioning experience are included. These are not intended to be exhaustive because a full lessons learned database is beyond the scope of this book. However, it is hoped that the thinking process behind the taxonomy proposed will help formulate the structure of a lessons learned database that can be populated with useful lessons in a way that will make the information contained in it both helpful and accessible to those responsible for decommissioning.

The tables that follow represent some ideas for the taxonomy of a lessons learned database along with some generic lessons of the type that may have application to any decommissioning site. It is suggested that using these generic lessons, decommissioning planners will be able to come up with their own detailed considerations of issues to be incorporated in their plans and issues to be avoided.

7.3.1 Lessons learned for government

LL reference	Lesson learned	Background
1.1	Establishing a publicly funded specialist decommissioning authority can provide an opportunity to recruit decommissioning planning and monitoring specialists to plan, manage, and oversee the national decommissioning program	While the organization that has operated the site has a great deal of essential knowledge about the site, they may be unlikely to have experience of decommissioning. Setting up a new body enables decommissioning skills to be brought in from other countries and industries
1.2	Understand that decommissioning is a process that creates radioactive waste and plan disposition routes for all expected waste streams, ideally before decommissioning starts or as soon as possible thereafter	Radioactive waste has a very negative reputation and the more that is produced, the less the public and the media like it. In fact, the faster decommissioning progresses, the faster the waste is created and this should be promoted as a positive aspect. Knowing the final destination of the waste will provide a better estimate of disposition costs and offers more accurate decommissioning cost estimates and timescales. It also avoids sudden increases in projected decommissioning cost estimates when it is found that waste volumes have been underestimated
1.3	Allocate adequate funds to the decommissioning program in line with the needs of the program and take steps to protect these from diversion to other national programs	Adopting an “open and honest” communications policy enables government to explain the decommissioning costs and to see how the funds for decommissioning sit alongside others such as education, health, and transportation

LL reference	Lesson learned	Background
1.4	Set up international cooperation with other nations who are already carrying out decommissioning work or who are about to start; IAEA can be a useful catalyst for this as can encouraging national nuclear trade associations to engage with equivalents in other countries	Many of the plants that are to be decommissioned in one country will have equivalents in others. Lessons learned, skills, and plant and equipment from these plants can help reduce local decommissioning costs and accelerate timescales (See also LL 1.6 and 1.7)
1.5	Obtain a good appreciation of the skills necessary for decommissioning and their availability in-country. Establish education and training programs to ensure that all skill levels are addressed	Some decommissioning planning does require highly skilled staff, while others require training in decommissioning specific craft skills. The curricula of engineering degrees should take account of the decommissioning industry, as should nationally accredited craft training schemes in relevant disciplines
1.6	Ensure that the decommissioning programs are sufficiently flexible to enable small changes to be made to provide capability in the local contractors that can be usefully deployed overseas	Decommissioning is a national industry; however, it has international potential. While decommissioning planning traditionally targets activities on a hazard reduction basis, where opportunities present themselves, it may be possible to change some priorities to allow national expertise and/or products to be developed to coincide with a need elsewhere and so enable local companies to bid effectively for overseas work
1.7	Align national research and development activities to recognize the requirements and timing of facilities to deal with decommissioning and waste management	Where national R&D programs exist, aligning their content and timing to the needs of the decommissioning program (and potentially overseas programs) will ensure that skills and products are available when and where needed

LL reference	Lesson learned	Background
1.8	Work with national and international security agencies to ensure that security is adequate without unnecessarily constraining the activities of the decommissioning entity	No one doubts the need for high levels of security in the nuclear industry. However, security is by its nature intrusive and limits freedom of movement. Careful integration of security policy with other management issues should provide adequate safety while recognizing the impact on the decommissioning program
1.9	Ensure that the legal basis of all regulators (safety, environment, security, safeguards, etc.) provides them with the tools necessary to regulate decommissioning effectively and put in place audit functions to ensure effectiveness and continuous improvement. Ensure that legislation provides for coordination of different regulatory organizations when needed	Nuclear regulation is normally enshrined in national law. As a result, the level of flexibility in interpretation and the options for the regulator to take exceptional steps to address a particular event may be limited. Decommissioning requires more flexibility in regulation than normal operations, and it may therefore be necessary or desirable to amend the law to address decommissioning specific issues. At all times, however, governments should ensure compliance with IAEA's Fundamental Safety Principles (SF-1)—principle 2, which describes the role of government

The lessons learned entries below in Section 7.3.2 refer to the lessons for the funding agency. In many cases, and in particular for the decommissioning of former research sites, the funding agency will be the national government, in which case the lessons learned for government will apply to the funding agency and vice versa.

In some cases, the funding agency is a separate entity such as the European Bank for Reconstruction and Development (EBRD) or World Bank in the case of the decommissioning of former facilities in Eastern Europe, so the lessons for the funding agency may be different to those for national government. Nonetheless, it would be appropriate for both entities to consider the lessons learned from both sources when making decommissioning plans for facilities in their countries.

In the future, it is likely that the responsibility for providing the costs of decommissioning nuclear power plants will rest solely with the utility that constructed and operated them. In these cases, looking ahead up to 60 years, decisions made during the design stage of a new plant may have a massive impact on the ease, timing, cost, and dose uptake associated with the decommissioning at the eventual end of life of the plant. One generic lesson learned about decommissioning that applies to all areas is that it is never too early to begin to consider the decommissioning of a nuclear facility, and considering the ease or ability of a plant to be decommissioned should be an activity that is undertaken when new plants are designed and when modifications are being made to existing plants.

7.3.2 Lessons learned for the funding agency

LL reference	Lesson learned	Background
2.1	Ensure that decommissioning plans are prepared by organizations who have experience in decommissioning and have these plans peer reviewed by a separate, suitably experienced decommissioning company	When funding agencies are arranging for the preparation of decommissioning plans, it is customary that they engage the services of specialists to prepare these. However, having a financial background, they may be tempted to use specialist legal/financial/management consultants. While such support is necessary, it is important that they also engage the services of experienced decommissioning consultants/contractors to ensure that the plan is safe and technically viable in order to minimize risks of all types
2.2	Where funding agencies are using international funds, consortia are often established involving companies from several countries. The main qualification for membership of such a consortium should nonetheless be competence and experience, rather than nationality	

7.3.3 Lessons learned for the site owner

In Section 7.3.3, it is assumed that the site owner and licensee are different organizations. Where this is not the case, the lessons learned in Section 7.3.3 can be combined with those in Section 7.3.4.

LL reference	Lesson learned	Background
3.1	A well informed, "make/buy" decision is necessary for all activities, including the overall responsibility for the decommissioning operations	Historically, in most countries where nuclear decommissioning has been tackled, the initial plans involved the use of the facilities' former operations staff to transfer to decommissioning. While there is a definite role for such staff, they cannot be assumed to be able to change from operations to decommissioning without training, and often without some major cultural shift. The augmentation of the former operations staff by the inclusion of experienced decommissioning staff from other companies and often other countries should be considered
3.2	Give serious consideration to the appointment of an experienced decommissioning agency with wide experience to conduct and manage the decommissioning activities on the site	Experience has shown that the introduction of experienced staff from outside the company, if properly prepared for and managed, can have a very positive effect on safety, performance and cost
3.3	When selecting support contractors to enhance the skills and performance of the staff formerly responsible for the operations of the site, it is important to ensure that these staff are fully aware of the legal and regulatory frameworks of the country where the decommissioning will take place	Typically, experienced support contractors will be brought in at several levels across the decommissioning organization, but they will certainly include senior staff. Regulators are rightly concerned about ensuring that those who set strategy and direct work are fully familiar with the regulatory framework of the decommissioning country
3.4	In considering 3.3 above, it is important to maintain compliance with the IAEA Fundamental Safety Principles (SF-1), particularly principle 1, which recommends that "the prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks."	In decommissioning, although the facilities were built and activities conducted in the past, the decommissioning process and the organization carrying this out are interpreted as being responsible for giving rise to the radiation risks

LL reference	Lesson learned	Background
3.5	Ensure that, where practicable, all historical information and recollections of former, possibly retired, employees, is captured, checked, and recorded while those with the information are still available to supply it	Usually, individuals who were employed at a decommissioning site will have memories of building layout, contents of cells, results of incidents, and many more recollections that could be very important for the preparation of safe and effective decommissioning plans. However, care must be taken to ensure that the accuracy of such recollections is checked
3.6	Prepare and implement a stakeholder engagement plan	One of the consequences of decommissioning is the creation of radioactive waste. It could be said that waste is the product of decommissioning, but it has a negative press. Ensuring that those local to the site are adequately knowledgeable about the decommissioning activities and the details of the waste produced will go a long way to reducing fear and encouraging support for the site's policies and program
3.7	Contribute to preparing and implementing a socioeconomic development plan	Decommissioning programs are directed towards removing the plants that once constituted the decommissioning site and generally provided much local employment. The removed if jobs come along with the removal of these plants. In most cases, it is not the job of the site owner to find an alternative use for the site, but the owner should work closely with local and national government agencies in an effort to tailor decommissioning programs to match potential reuse of released land for alternative purposes and to facilitate redeployment of the skills of the locals to support other business opportunities

LL reference	Lesson learned	Background
3.8	In preparing the contract for the appointment of a site managing agency, it is important to provide the flexibility necessary to cancel the contract and to retake control of the site in the event that the performance of the contractor falls short of what is anticipated	In Section 7.2.8, the decision by the United Kingdom's Nuclear Decommissioning Authority to terminate the contract for the management of the Sellafield site, previously held by Nuclear Management Partners, was described. While the contract conditions appear to have played no part in the performance of the program, the termination arrangements in the contract were such that it was possible to terminate the contract "for convenience" while providing time for a transition period of over one year

The regulatory regimes across the world differ markedly from country to country. As a result, some of the lessons learned may not be relevant in all countries. It will be necessary for decommissioning planners, when using this book, to establish the nature and extent of relevance of any of the suggested lessons in the following table when embarking on the preparation of decommissioning plans.

7.3.4 Lessons learned for the site licensee

LL reference	Lesson learned	Background
4.1	Ensure that there is complete independence between the decommissioning contractor and the site owner	Regulators, whether safety, environmental or security, are always concerned to ensure that no undue pressure can be placed on those who operate the decommissioning processes by the site owner in those cases where the two are different
4.2	Train staff adequately for all tasks they will be required to perform and ensure that they understand not only what they are required to do but why they are doing it in a particular way. If possible, those who will perform decommissioning tasks should be involved in the preparation of the method statements to ensure that they understand as many of the hazards, risks, and mitigation arrangements as possible	In decommissioning, procedures are often devised as they are needed, whereas in normal operations, it is possible to predict a wide spectrum of activities that an individual may be required to perform. In many cases, the hazards associated with decommissioning are much higher than is the case with routine operations and the opportunities for things to go wrong are greater. Training must therefore cover what is to be done and why

LL reference	Lesson learned	Background
4.3	Revisit the procedures of the site owner/previous licensee to ensure that they are acceptable and update/replace them where this is found to be appropriate	When site owners appoint a new decommissioning contractor, the staff will be familiar with the site owner's procedures. If benefits are to be derived from the appointment of a new decommissioning contractor, it follows that the previous working methods will change in some way. Staff members need to be aware of the need for change and the new decommissioning contractor needs to check that the revised procedures are understood and being implemented by all staff
4.4	Culture and safety are closely related. No improvements in safety can be assumed by preparing revised working methods alone. Only if the culture of the staff is aligned to the delivery of improved safety performance will real improvements be obtained	The transition from operations to decommissioning is a major step for the former operations staff of a site, and decommissioning in most cases is a more hazardous activity than routine operations. The responsibility for safety at all times, and in particular during this transition period, is vested in the licensee. Assessing the current staff culture and developing a culture change program is an important precursor to introducing revised working methods and safety management systems
4.5	Prepare and maintain an accurate waste breakdown structure	Decommissioning results in the generation and subsequent management of radioactive waste. It is important to predict the location, quantity, and nature of all waste streams that will be generated

7.3.5 Lessons learned for regulators

LL reference	Lesson learned	Background
5.1	Review and adapt the regulatory regime as necessary to ensure that it is fit for purpose for the decommissioning program	In all countries with a nuclear program, the regulatory regime was established to regulate the design, construction, commissioning, and operation of the program. Decommissioning usually follows many decades of such operations and it is important to review the legal framework against which regulators will operate during decommissioning, to ensure that this regulatory regime, developed for construction and operations, is appropriate to support safe and effective decommissioning
5.2	Prepare training programs for the regulatory staff to ensure that the techniques and standards they apply when regulating decommissioning operations are appropriate to decommissioning work and not based on the regulation of operations	Even if a review of the high-level legal arrangements for nuclear regulation shows that no changes are necessary to the national laws, the interpretation of the legal arrangements for decommissioning are likely to need to be reviewed and new interpretations of fitness for purpose derived. Regulatory staff will then need to be trained on these new interpretations so that they are able to regulate decommissioning activities to ensure safe, environmentally acceptable decommissioning while enabling this work to be carried out efficiently
5.3	Work with the site licensee to take his experience on board when preparing the techniques and standards referred to in 5.2 above	In many cases, the novel techniques that will be needed to support decommissioning will be prepared as the decommissioning work progresses. In normal operations, it is customary for detailed method statements to be prepared, submitted, and where local regulations require it, approved by the regulator. In decommissioning, the activities typically involve a larger number of small steps to be taken due to the greater number of unknowns. If the regulator works closely with the licensee to understand the decommissioning activity, its problems, hazards, and risks, it is more likely that the combined requirements of legal compliance, safety, and efficiency will be achieved

LL reference	Lesson learned	Background
5.4	Liaise with the international decommissioning community	While the nuclear regulatory frameworks are nationally based and differ, sometimes significantly amongst nuclear nations, the technical, safety, and environmental problems do often have a degree of consistency. Just as opportunities should be taken by the site owner or licensee to take advantage of international decommissioning experience, similarly, the regulators should consider the regulatory experiences and technical solutions found to address common and unique decommissioning issues and deploy these in the regulation of activities in their home nation. IAEA and organizations such as WENRA have a major role to play in disseminating lessons learned amongst national regulators

Section 7.3.6 deals with lessons learned for site decommissioning contractors. The detailed day-to-day problems experienced in nuclear decommissioning are often found by these contractors, and the potential for this section to run to many volumes clearly exists.

In this publication, the lessons learned have once again been confined, so far as possible, to the generic lessons to be learned by decommissioning contractors, rather than to repeat the many lessons learned databases that already exist.

This in no way suggests that such databases are of limited use. The types of lesson learned here are intended to be considered in addition to those of a detailed technical nature rather than to replace them.

7.3.6 Lessons learned for site contractors

LL reference	Lesson learned	Background
6.1	Raise awareness of decommissioning staff of the management processes of the licensee and insist on compliance	It is common that the staff of the decommissioning contractors do not understand the management processes of the licensee and often think they are unhelpful and even absurd. The degree of paperwork and associated controls exercised by the licensee are often considered as hurdles to be overcome rather than the principal means by which their personal safety and that of the other occupants of the site, the local community, and the environment are safeguarded

LL reference	Lesson learned	Background
		Staff must understand that if a control seems unreasonable, they probably do not understand its background and instead of finding a way around, they should instead seek additional information to help them to appreciate the reason for the control
6.2	Encourage and incentivize decommissioning staff to suggest alternative methods of carrying out specific tasks	If method statements for decommissioning work are not prepared by individuals who have experience of actually doing the decommissioning task, then activities that they may consider straightforward may in fact be extremely difficult in practice. Decommissioning contractors should be afforded the opportunity to comment on the methods and have the facility to stop the work, report difficulties, and to suggest easier, safer alternatives. Making some financial incentive for such ideas is likely to provide encouragement for staff to follow this recommendation
6.3	Train staff regarding the role of radiological PPE	In the past when film badges were used for dosimetry purposes, it was common to find them pinned on operatives' jackets the wrong way round. While modern Thermo Luminescence Dosimeters (TLDs) are less sensitive to orientation, examples have been found where these are kept in toolboxes or in pockets because the staff did not fully understand their role or how they work
6.4	Be sensitive to the differences in culture between nuclear operations staff and those who also work in traditional industries, whether for decommissioning or construction	Culture plays an important part in the management of decommissioning contractors. Those who formerly operated a nuclear facility were aware of the difference between working in such a facility as compared with say a conventional power plant. Decommissioning contractors' backgrounds are often based on conventional activities such as excavations, scaffolding, and demolition. Their approach to safety and the use of PPE may therefore reflect traditions in conventional industries. One of the most frequently asked questions on OHAS courses is, "Can I wear my hard hat backwards?" While suitable head protection can indeed be worn in this way, the act of asking the question may itself be an indicator that the questioner is more interested in appearance than safety

LL reference	Lesson learned	Background
6.5	Build in time in proposals to allow for the inefficiencies that attend the cautious approach to nuclear decommissioning in order to avoid pressures to meet time targets	Dismantling nonnuclear facilities is often able to be achieved in a straightforward fashion with traditional cutting and demolition skills employed. The extra time needed to decontaminate components, walls, pipework, etc. when dealing with an active plant needs to be taken into account. Furthermore, the time limits for operatives working in elevated radiation zones need to be adequately factored in when assessing the time required for an otherwise simple task

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Emerging technologies

8

H. Farr[1]
Radiation Safety and Control Services, Stratham, NH, United States

8.1 Introduction

As noted in the preface, technological breakthroughs in decommissioning technologies have been slow to emerge, and despite international efforts to collaborate and focus on research and development of technologies for decommissioning, collaboration has been limited and the industry is still largely reliant on adopting technologies developed and refined for other industries. Some government agencies such as the United Kingdom Nuclear Decommissioning Authority (NDA), the United States Department of Energy, and Japan's Atomic Energy Agency along with companies such as Electricite De France have been the exception and have aggressively fostered large-scale R&D and adoption of new technologies to reduce the cost of the vast fleets of facilities they are responsible for decommissioning. Unlike the R&D focused work I have previously written about [1–3,176] this chapter is more pragmatic, focusing on existing emergent technologies that either are being used for nuclear decommissioning or that can be brought to bear on the endeavor. As stated in the preface, information management in the forms of data collection, organization, and sharing, as well as robotics and the use of lasers are some of the emergent technology breakthroughs that are benefitting active decommissioning projects. However, there are many other emergent technologies such as the use of drones, geostatistics, building information models, wireless network technologies, etc. that are also being used to increase decommissioning safety and efficiency. This chapter will discuss the various types of emergent technologies available for executing nuclear decommissioning.

8.2 New technology integration into the continuous improvement process

Human beings are creatures of habit and rely heavily on their experience when making future plans. In the not-so-distant past this was highly individual and local, with nuclear power activities being planned based on personal experience and recollection from past activities. As a result, maintenance and refueling outages were commonly performed over many months with no systematic tools or processes to capture documentation for repetitive tasks and activities or lessons learned. In part this was a technological issue

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[1] Harvey Farr gained experience using and deploying robotics at Connecticut Yankee and has written reports and articles on use of robotics for decommissioning. He has also written reports on decommissioning management for EPRI and on needed R&D for decommissioning for the OECD.

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because typewriters, carbon copies, drafting tables, and mimeograph machines made data capture, document revisions, and sharing of information slow and expensive. The advent of personal computers, modular data storage, and computer networks in the 1980s and 1990s enabled the advances in activity planning and incorporation of lessons learned that drove the increased performance and efficiency reducing commercial nuclear outage times from months to weeks. Word processing, databases, and planning and scheduling and access control software enabled more detailed planning and execution documentation to be generated and stored cheaply for future use on the same or similar tasks. It also enabled the information to be gathered, evaluated, and shared collectively in a way that planning was based on collective input and objective fact.

This information was used to develop and refine the continuous improvement process for use in the project planning life cycle. Documentation and schedules from previous outages or activities are archived and used as a starting point in the planning life cycle; lessons learned are also captured and archived during performance and close-out of a work activity. Lessons learned and input from crossdisciplinary planning teams are used to refine and integrate plans and schedules of upcoming activities in order to reduce risk and gain efficiencies, and lessons learned are captured and during performance and close out of the activities for future use and archiving completing the project planning life cycle and implementing the continuous improvement process [4,5].

As a result, US nuclear power plant performance went from load factors of 56% in 1980 to 66% in 1990 and 81% in 2012. Looking globally at 400 power reactors over 150 MWe for which data are available, the world median capacity factor increased from 68% to 86% from 1980 to 2000 and averaged at 85% since. In 1990 the reactors of the top 25% performers of the world had load factors of 75%; the top 25% of the world's reactors have load factors of more than 90% [6]. Although this process has been highly effective and useful, it is imperative not only to capture and consider lessons learned into planning activities but also to systematically integrate evaluation of emerging and available technologies and lessons learned from the broader industry and even unrelated industries in order to accelerate the improvements in efficiency and performance.

One of the key lessons learned from implementing new technologies in decommissioning is the importance of small-scale testing and use of mock-ups to allow for integration and application of the continuous improvement to the technology use in low risk, low impact situations. It is also important to use the multi-disciplinary planning life cycle when procuring, planning, and using new or emerging technologies to integrate and improve them incrementally, as was described above for outage and maintenance activities to fully realize the long-term benefit of making this part of the process.

8.2.1 Continuous improvement process in nuclear power

It is necessary to start the continuous improvement process to decrease near-term costs of decommissioning nuclear facilities. An example of the successful application of a continuous improvement process is the refinement of work planning and technologies that dramatically shortened commercial nuclear power refueling and routine maintenance outages as well as the nonroutine outages for upgrades such as steam generator, reactor head replacements, and more recently power upgrades replacing

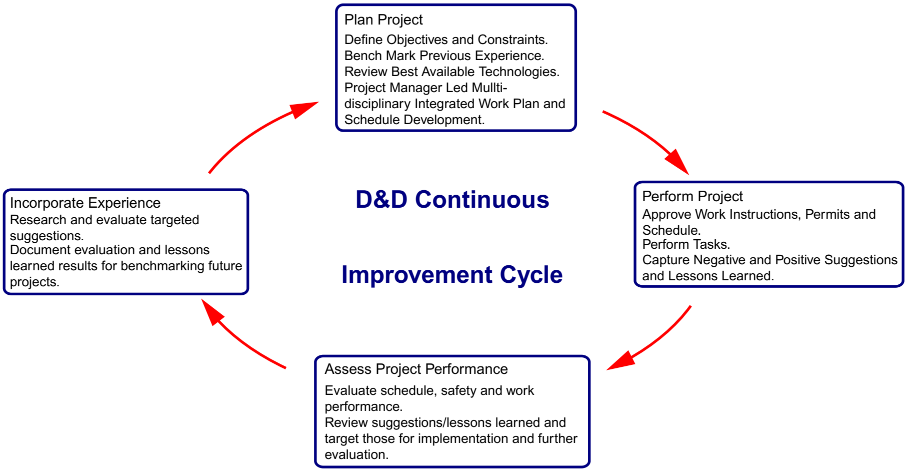

Fig. 8.1 D&D Continuous Improvement Process Phases and Elements.

secondary side components [7]. The technology and efficiency gains in the 1980s and early 2000s came from a systematic approach to work planning and execution with the feedback of lessons learned, which resulted in incremental improvement to iterative processes. Due to the sporadic nature of decommissioning projects, which have been isolated from each other by time, distance, closure criteria, program implementation methodologies, and commercial contract obligations, the continuous improvement process has remained largely unharnessed in nuclear decommissioning (Fig. 8.1).

If we are going to decrease the time and costs of decommissioning, it is essential that we start gaining knowledge and experience with technologies that are already available to capitalize on the rapidly expanding capabilities of emergent technologies over the next decade. Given the increasing decommissioning cost estimates and the anticipated near term liability associated with currently shutdown and the planned future shutdown of facilities, there are two major objectives for the near-term R&D Initiatives;

1. Develop technologies for better, cheaper, and faster D&D (Decommissioning and Dismantlement).
2. Implement the technologies in the supply chain and in the field at actual D&D projects to start and maintain a continuous improvement cycle.

8.2.2 Lessons learned from successful and unsuccessful adoption of new technologies

8.2.2.1 Unsuccessful or challenging new technology projects

The history of reactor internal segmentation projects at nuclear decommissionings in the United States is an example of unsuccessful and challenging attempts to integrate new technologies into decommissioning. Reactor internal segmentation attempts to date have encountered severe challenges and limited success with extensive project delays and best performance still being lengthy multi-year projects. Attempts have focused largely on three cutting technologies: plasma arc (PAC), abrasive water jet (AWJC), and mechanical cutting with supplementation by use of electric discharge machining (EDM) and metal disintegration machining (MDM) [8,9]. High airborne radioactivity and water clarity issues leading to excessive waste generation and high personnel radiation doses were encountered at Yankee Rowe from plasma arc cutting. SWARF generated from cooling of the cutting gases underwater lead to poor visibility and plated out high activity particulate in the reactor cavity, resulting in dose rates of 0.01 to 0.1 Sv/h on items in and around the reactor cavity. In addition, the hot cutting gases also bubbled to the surface where an attempt was made to capture it by a floating hood hooked to HEPA ventilation. This resulted in the floating hood being contaminated to the dose rates mentioned above and required frequent HEPA filter changes and work stoppage due to clogging and filtration media dose rates in the 0.01 to 0.05 Sv/h range. Based upon that experience, abrasive water jet cutting was used at Maine Yankee, Connecticut Yankee, and San Onofre 1.

These projects met with challenges capturing the secondary waste generated, slower cutting speeds than anticipated, and larger secondary waste volumes than planned on. As a result, the industry shifted to use of mechanical cutting methods that consisted of underwater lathing and cutting for internal segmentation of Rancho Seco, Plum Brook, and Zion Units 1 and 2 internals. Again, problems were encountered on each of these projects with cutting speeds and performance, with the most recent efforts at Zion requiring numerous tool design changes during performance of the Unit 1 and 2 projects. In general, there are several common themes that plagued each of these projects: the hardness of neutron activated reactor internals compared to conventional stainless steel led to inadequate tool designs and planned cutting speeds and the failure to develop and test robust secondary waste capture and water clarity filtration systems. A complete, thorough, and candid assessment of the lessons learned from each of these projects for integration into the continuous improvement process is advisable when implementing these technologies or new technologies such as arc saw or laser cutting on future projects.

8.2.2.2 Successful new technology projects

New technologies have been successfully deployed on decommissioning projects and at operating nuclear power plants. These successful applications of technology include wireless and paperless document control, work execution, and communication systems that are being integrated into construction projects and operating nuclear power plants. Technologies successfully deployed at operating facilities such as electronic work packages and radio frequency ID (RFID) inventory and tracking are applicable to decommissioning facilities. Decommissioning and operating facilities rely heavily on detailed procedures and work packages to safely and compliantly perform work. Work packages can be many hundreds of pages with sequential step sign offs and many attached permits and drawings that are carried into the field for the performance of work. Wireless document control, information distribution, and communications systems are being adapted to streamline the work planning and execution. These technologies are being deployed by nuclear power plant operators to gain efficiencies and lower costs [10]. The system uses media devices such as a tablet or portable PC that would provide significant maintenance and work management process improvements. The mobile device would be fully self-contained with all available resources. An eWP (electronic Work Package) also offers the ability to have user defined work instruction detail based on the input of the worker [11]. Wireless coverage is a challenge in nuclear facilities; however Electric Power Research Institute has recently tested a distributed antenna system (DAS) network at a decommissioning power plant in the United States [12]. The demonstration included testing in the 700 MHz and 2.1 GHz LTE bands to evaluate RF propagation by a DAS using radiating cables and showed that 100% coverage is achievable.

CEA (French Alternative Energies and Atomic Energy Commission) has invested in R&D initiatives to bring emergent technologies to bear on decommissioning. These initiatives include remote control operations, measurement of nuclear wastes, characterizations for investigations, process engineering, 3D models, information systems, nuclear ventilation, etc. Methods and software were also developed for better waste management [13]. CEA has used 3D CAD models and geostatistics to streamline characterization and remediation projects by reducing the sampling to only that which is needed to achieve high confidence levels so that the location and distribution of contaminants in building materials and the environment are accurately determined, for remediation planning and compliance with site release criteria. The use of noninvasive data collection methods such as gamma cameras, alpha cameras, and auto-radiography for beta emitters, as well as Laser Induced Breakdown Spectrometry (LIBS) that uploads to 3D CAD models, enables the rapid characterization of radiation fields and surficial contaminants within facilities. This enables geostatistics to be applied to distinguish between areas where data indicates the contaminants are characterized with high confidence and those that require additional sampling. CEA is further streamlining the process by using robotics to deploy these measurement devices. Location-aware wireless systems such as those used in health care [14] and other industries [15] are commercially available and can provide x,y,z coordinates and time signatures to the data collected by these measurement systems. These systems are commercially available to be used at decommissioning facilities and the cost and accuracy continues to improve. CEA is modeling and mapping operating facilities with higher precision than required to map characterization data to a 3D model of a decommissioning facility [16] (Fig. 8.2).

Fig. 8.2 CEA is using 3D models and characterization data for simulation of scenarios and training [13].

These technologies have been used to gain efficiencies in the decommissioning of the Kursk Power Station in Russia, where 3D CAD modeling has been used [17].

Robotic and remotely operated equipment has been used successfully in the Fukushima disaster response to clear debris and create access [180]. These systems are a current capability [18,19] that can be applied to nuclear decommissioning. Remotely operated heavy construction equipment such as the excavators, trucks, bulldozers, etc. used to clear debris from Fukushima Daiichi site can be used to more safely and efficiently conduct interior and exterior demolition of site structures and systems. Heavy equipment was operated remotely using X-Box controllers from command modules in sea/land containers up to 2 km away. The expansion of similar capabilities for the construction industry in general is being vigorously developed and investigated [20,21]. The use of this type of system coupled with location-aware networks and building information models has made it feasible to perform decommissioning largely from command centers.

Robotics were also successfully used to clean the reactor cavity and tanks, package high dose rate wastes, and perform demolition tasks such as removing the cavity liner at the Connecticut Yankee decommissioning [22].

The major lessons learned from successful and unsuccessful adoption of emergent technologies are the following:

- Importance of integrated multidisciplinary planning and project management
- Selection and management of vendors
- Active management even for fixed price contracts; decommissioning project personnel support and involvement is always required
- Design and fabrication review and management, mock-ups, and field testing, prior to project deployment
- Implementation of continuous improvement during planning and performance
- Importance of post job review and lessons learned as project milestones are completed or challenges are encountered

8.3 Broad spectrum technologies

There are many technologies emerging in nonnuclear markets that can be adapted and deployed to benefit decommissioning efforts. These technologies are broadly applicable and could greatly benefit decommissioning reactors and nuclear facilities globally. “Broad Spectrum” technologies have application and impact across all or most phases of decommissioning and provide capabilities and architecture to support and enable other D&D activities. They are centered around available and rapidly developing technological capabilities that are being integrated into nuclear reactor operations and construction projects such as

- Wireless data sharing and work platforms
- RFID Tags and Wi-Fi Tags
- Location-Aware Networks or Real Time Locating Systems (RTLS)
- Building Information Models (BIM).

Examples of applications are wireless communications and data sharing technologies as well as scanning and pattern recognition technologies. Communication systems that are “location aware” allow Internet of Things (IoT) sensors, Wi-Fi tags, and RFID tagged data to be integrated and uploaded to the BIM in real time, providing 3D CAD mapping of the data and allowing situational awareness capabilities to be brought to bear on decommissioning planning and coordination, project status, safety interlocks, and the mapping and tracking of data [178,179]. Building information models are 3D CAD models of the site with data linked to coordinates. Use of these models allows project management planning and status to be maintained and users of tablet based work control systems to know where they are within the BIM and have access to all the information about structures or components in their vicinity.

These are also essential platforms for developing interlocks and operator assistance systems required to safely and efficiently deploy remotely operated, autonomous, and semi-autonomous heavy equipment and advanced laser based cutting, characterization, and decontamination technologies and to integrate many other emergent capabilities into D&D. Artificial Intelligence software can data mine and process massive amounts of information like plant drawings, system descriptions, procedures, and manuals and organize it within the BIM. Expedited 3D CAD enables the BIM to be constantly updated, automating project management status and situational awareness and allowing IoT and RFID data to be tagged to up-to-date 3D CAD models. This can greatly increase the mapping of radiation and contaminant data and facilitate use of geostatistics and kriging to map levels in 3D. In addition to safety and logistical considerations the emergence of these capabilities will greatly increase information sharing and project execution efficiency.

8.3.1 Wireless cloud communications

Platforms are available to share and archive data using iPhones and tablets in the field with Wi-Fi enabled applications. Work packages and all the supporting procedures, drawings, etc. are instantly available from archives in the cloud and allow schedule tracking as well as field changes and package updates. Systems are available for integration into work packages that allow access to drawings from any device [23]. Exelon’s e-work package initiative is an excellent example of the use of such systems at nuclear power plants for radiation surveys and work packages and can be adapted to decommissioning [24]. Wi-Fi enabled, cloud based construction and nuclear mobile asset management work platforms such as Procore [25], Curtiss Wright Ovalpath [26], and Bently’s AssetWise [27] are currently in use for mobile device access and updates for project management, document control, paperless work process, and asset tracking [173]. This allows field updates and revised documents to be instantly available without the records management removal of outdated documents and distribution of revised hard copies throughout the organization. Architects, engineers, subcontractors, and other team members have instant access to the latest information either in the office or out on the construction site [28]. Choate Virtualworks software uses hyperlinked drawing sets that allow operations staff and subcontractors to have the latest information instantly at their fingertips, with documents and notifications quickly synched to the jobsite through ShareFile and construction-based smartphone apps.

Everyone accessing the work packages, drawing, procedures, etc. from their mobile devices are viewing the current versions at the same time once the revised document is uploaded to the system. Project management and work execution software such as Procore also provide project management schedule and budget dashboards in real time.

Another technological concept that is ready for integration into decommissioning projects is the Internet-of-Things (IoT) [29]. This entails embedding of sensors and chips in personal, home, and industrial devices, such that data is collected and transmitted real time to on-site servers or servers in the cloud [30] for storage and analysis [31]. In a D&D setting, this could be water processing pump speeds and flow rates, area radiation monitor dose rates on demineralizer beds and filters, weights, locations, and dose rates on waste containers, hours of operation, fuel use, and location of equipment, or even personnel identities and locations [32]. Using IoT capabilities also enables radiological and hazardous material data to be transmitted and stored in the cloud in real time from radiation survey instruments like data loggers or 3D gamma cameras [33,175] and from industrial safety instruments such as oxygen, explosive gas, volatile organic carbon monitors, or XRF (X-ray fluorescence) data [34,35] (Ref. [36] A good example of an application of IoT technology was during the Japan nuclear catastrophe, when numerous Geiger counters owned by individuals were connected to the Internet to provide a detailed view of radiation levels across Japan [37]. Wireless sensors can also be used to monitor performance of modular equipment used to replace the original plant hard-wired systems such as HEPA units, water processing skids, and liquid and gaseous effluent discharge information. Development of an affordable, adaptable wireless communication system that is easily deployed and maintained in a D&D setting is critical to ensure the technologies discussed in this article can be brought to bear on decommissioning [38–44]. ABB has a modular, solar powered, private wireless system for use in open pit mining. The ABB Tropos wireless mesh technology greatly reduces the need for large towers and in some cases eliminates it altogether. Routers, deployed on trailers around the pit, "discover" each other automatically and provide ubiquitous coverage for the entire pit. When the pit topology changes due to new mine sites, the trailers are simply moved to new edges, creating coverage for mission-critical applications within minutes instead of the months needed for a tower-based design [45] (Fig. 8.3).

For a broader understanding of the IoT, cloud computing and the opportunities and challenges afforded by the coming massive increase in connectivity the article “The Internet of Things—Converging OT and IT” by Gordon Feller [29] is highly recommended for a well thought out and concise overview of the topic. Distributed antenna system (DAS) networks described above can also be used to augment these systems in areas where signal disruption is a challenge [12].

Radio frequency identification (RFID) tags can be used to tag information to an object or person. This allows additional data to be stored and retrieved in the cloud such as a person’s training and qualifications, signature authority, the chain of custody information on samples, or equipment identification information. Some nuclear power plants are using RFID tags on containers storing outage equipment to allow a read out of their contents from a handheld device [46–48]. Similarly, information about equipment can be tagged to an RFID that uniquely identifies that piece of equipment and information related to it. Monitors that sense RFID tagged safety equipment for personnel accessing

Fig. 8.3 ABB Tropos Solar Powered Wireless Router [45].

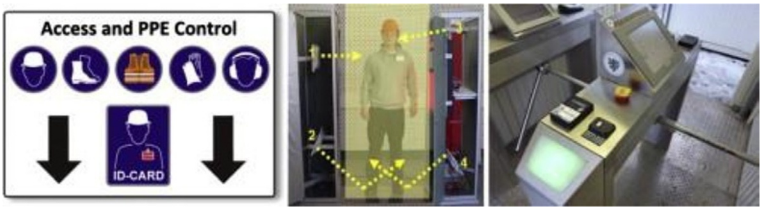

Fig. 8.4 RFID Tagged PPE Portal Monitor [49].

construction sites are already being tested and developed [49,50]. AREVA is installing RFID tags on nuclear reactor welds in France in a BIM application [51]. Nuclear Street reported that "The Beweis RFID (radio-frequency identification) tag lets inspectors identify pipe welds and their accompanying radiographic images while calling up quality control data, including the weld date, serial number, Global Positioning System (GPS) coordinates, pipe diameter and the welder's name. The software that runs the system is hosted on a local server [51]. The French government's PACA labs is testing the project, known as Be-Tag." Tags that are extremely rugged and resistant to extremely high radiation doses are also being developed in the United States [51,52] (Fig. 8.4).

8.3.2 3D modeling and building information model uses

Building information models (BIM) allow data and information to be organized and tracked relative to 3D CAD models of the site. This allows location data to be tagged to x,y,z,t coordinates and enables tracking of the facility physical state, equipment, personnel, characterization data, and material handling packages throughout the project. Tagging characterization data to the BIM supports geostatistical modeling and planning. BIM model software packages such as Russia's Neolant [53] or general architect/engineering construction applications like Autodesk [54] are widely available and are being used at operating power plants and on construction projects as well as for monitoring infrastructure like bridges. These models also allow decommissioning planning to be done in 3D using systems like GE Hitachi's use of MicroStation to plan decommissioning of reactors [55]. Sellafield has adopted BIM for decommissioning planning [56]. Multidisciplinary coordination was facilitated at Sellafield by the BIM. The 3D visual model of the plant simplified coordination of disciplines performing work. This also resulted in significant time savings in internal and external stakeholder review of drawings and information. BIMs enable better project management. Choate construction describes the benefits of BIMs for project management [28].

Spatial Coordination/Clash Detection: Once a building information model (BIM) has been created, software can be used to verify, coordinate, and check the modeled building components and systems against one another. This process is typically done before the fabrication of components has begun, ensuring all parts of the building fit together correctly. It can also be used to verify the demolition process is planned and integrated.

Model-Based Scheduling: By combining building information models and the project schedule, management is able to watch the schedule come to life through 4D animation. Once a 4D schedule has been created, the team can analyze alternative schedule paths to find the best method for the project. They can also benchmark updates to the BIM to the schedule and monitor progress and status using the BIM.

As-Built Modeling and Facility Management Data: Building owners and operators can benefit from the project models and data collected during the design and construction phases. Information and data about the building's spaces, systems, assets, and components are recorded and updated during the construction process. The same capability can be brought to bear on the decommissioning process for D&D tracking component removals, changes in physical layout, characterization data, equipment locations, and material package locations.

Constructability & Waterproofing Models: The individual 3D computer models of detailed project areas allow constructability studies. These highly intricate models allow the entire team to understand how the pieces fit together and are used as a way to communicate about a specific part of the project with designers and subcontractors. In the same way, they can be used to understand the disassembly and material handling and work area conflicts at a decommissioning facility. Critical path items such as crane time can be analyzed and scheduled in detail, allowing additional needs to be identified early on in the project.

Model-Based Digital Layout: This process allows for the placement of any modeled building component with extreme accuracy, resulting in near watch-maker precision and the highest levels of quality control when coordinating critical components and/or equipment. BIMs allow field changes to be immediately available to the organization.

3D Laser Scanning: 3D laser scanners allow the capturing of as-built conditions by recording all elements of the building and translating them into point clouds. These point clouds are then used in conjunction with the BIMs to help understand the new design within its existing context or to verify installed components. This same technology can be used to update BIMs in the demolition process. There are also other systems like drone-to-map, light detection and ranging (LIDAR-to-map), and even photo- and video-to-map capabilities that allow the BIM to be easily updated.

There are separate technologies related to location awareness and 4D (x, y, z, time) computer assisted design (CAD) capabilities that augment the BIM [57]. Satellite global positioning capabilities are already well known enabling Global Positioning System-based navigation and tracking on cell phones and driverless autonomous heavy construction vehicles like Caterpillar's MineStar system [58,59]. This technology is currently being used by control and monitoring systems for heavy equipment in construction, mining and agriculture [18,60–64]. The coupling of location awareness of the bulldozers, hauling trucks, etc. within a 3D CAD model of the mine is being used by heavy equipment manufacturers to enable tracking of equipment and personnel locations [65] and to allow remote, semi-autonomous, and fully autonomous operation (i.e., no operator) of the equipment along with situational awareness command and control tracking capabilities from monitors in a control room [66,67,19]. The BIM provides the spatial controls for operation of the equipment which use the GPS location within the 3D CAD model for navigation. It can also be used to set interlocks that stop vehicles from operating in or transiting to areas within the BIM. Think of it as a virtual reality game that is tied to the physical layout of the room, area, or site.

Passive RFID tags can be used to store information about a container, a person's training or qualifications, etc. Active RFID tags, also called Wi-Fi tags, are larger (e.g., wrist watch size) than passive RFID tags (less than 1 centimeter) because they contain a battery and transmitter to also identify the location of the tagged item within the BIM. Miniature power sources and transmitters are under development, with the promise to shrink these devices to passive RFID sizes [38,39,43].

While accuracy to within a few meters is currently used in industries such as healthcare, New RTLS systems can locate a RFID or Wi-Fi tag to within a few centimeters. This will enable Internet of Things information to be tagged to physical coordinates in time and space throughout a decommissioning facility [32]. This means that both dynamic and real time data as well as facility design data can be linked spatially and made available for download and analysis in the cloud. This allows field measurements and activities to be tagged to the BIM to track personnel and equipment locations, contaminant measurements, package and tool locations, etc. in real time.

As discussed above, tablet based, paperless, work control, and document control systems that enable work orders, drawings, survey maps, etc. to be downloaded, completed, and updated in the field are currently in use at operating power plants and on construction projects. Scanning a bar code on a piece of equipment allows it to be identified and all document control information related to it to be downloaded to the tablet in the field. Wireless location awareness capabilities will eliminate the necessity of bar coding equipment because the active RFID will know where it is in the BIM and all the current information stored in the BIM on that item is available to personnel on their tablets, cell phones, and computers. Aspects like the weight, material composition, or a component or the weight and contents of a container tagged to the BIM are readily retrievable and can be used to set interlocks to prevent out of specification rigging tagged with RFID chips to be used or equipment not rated for the load to be used [181].

RFID technology together with 3D CAD/Geographic Information System (GIS) models are being used to locate and track buried commodities [68,69,177]. Knowledge of the physical location of the tablet, smart phone, etc. within the 3D CAD/GIS model enables the equipment to be identified based upon its coordinates and for data and information related to that location to be accessed, downloaded, and modified in real time. Radiation Safety and Control Services, Inc. has worked with Exelon to develop exactly that kind of system for groundwater protection and underground asset management using GIS/GPS based location awareness. A complete 3D CAD/GIS model of the site including outdoor above ground and underground commodities is developed that shows piping runs, duct banks, storm drains, pits, pumps, and valves and positions them in 3D space linked to each asset's information, which is stored in database format(s). By knowing the location of a tablet or smart phone, objects within a certain radius can be identified. Data collected in the field or through laboratory analysis is tagged with the 3D coordinates and uploaded in real time to the cloud. This is well-monitoring data, such as water level, pH, etc. Contaminant concentration data on a well or systems or inspection data, such as pipe wall (UT) inspections or geotagged and component tagged photos, collected real-time in the field are uploaded to the cloud and tagged with x,y,z,t signatures that correspond to the spatial location in the 3D CAD model of the site. The facility design and operation data as well as the IoT data are stored in a GIS database such that all the information related to systems, samples etc. within a certain radius of a location can be retrieved and the exact location of an underground component can be identified based upon the location of the user's tablet or cell phone in the CAD model (Fig. 8.5).

Thus, the coupling of IoT data, location awareness, and 3D digital models is already being used to facilitate information management and use of autonomous and semi-autonomous capabilities [20]. This will enable significant efficiencies and safety enhancements to be brought to bear on decommissioning when one thinks about the value of tagging and mapping data to a 3D coordinate system and the situational awareness and safety interlocks for remote and operator controlled equipment [183] that can be developed from this. Efficiency gains include elimination of the intermediate steps to map survey and contaminant data, automated schedule and status update capabilities, automated inventory of equipment and waste packages, and remote monitoring of equipment (Fig. 8.6).

In the construction and architect engineering realms, systems that capitalize on these capabilities are being developed into BIM technologies [70]. Capabilities are being developed to tag project completion information to the 3D digital model of a facility under construction to enable real time tracking of progress and completion status. This frees resources from updating schedule status because the status is tracked in real time and enables more focus on predictive scheduling and optioneering [71,72]. So instead of an I-beam placement being tracked on a construction project, the location of a tagged component, pipe, piece of equipment, etc. is tracked. The BIM knows when the plasma arc is in the work area or when the valve or pipe is moved, packaged,

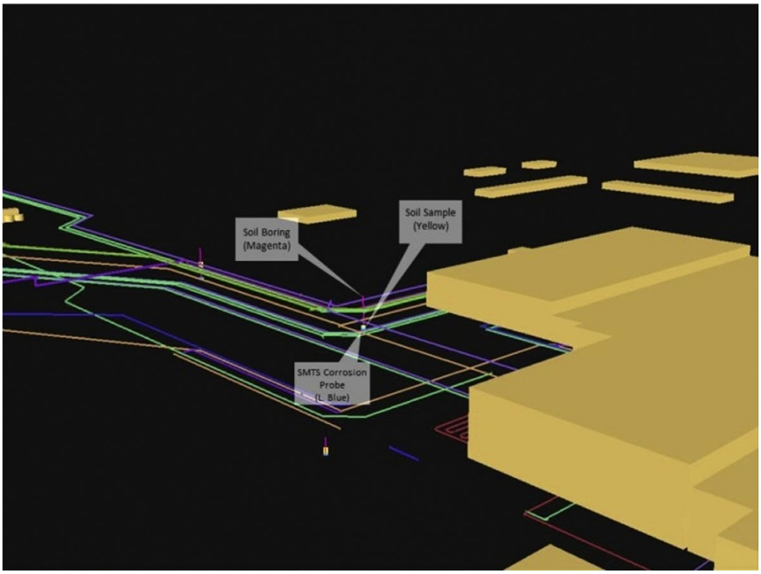

Fig. 8.5 Corrosion rate and cathodic protection asset management probes installed proximal to buried plant piping shown in a 3D GIS digital model. Courtesy of Radiation Safety and Control Services Inc.

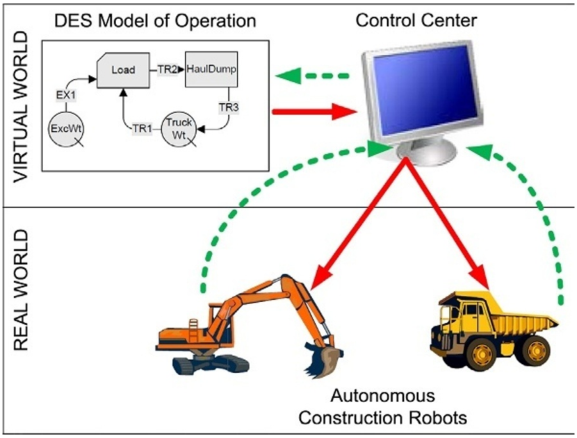

Fig. 8.6 Integration of Autonomous Robotics to Construction Sites from [20].

stored, and shipped. D&D can use the same BIM tracking and management capabilities currently used in construction. Physical installation of IoT tagged materials and items as well as real time tracking of work order information allows a real-time project status to be maintained instead of daily status meetings and schedule updates. This frees management and personnel time to plan forward rather than capturing data and status in the rearview mirror. BIM technologies with sensors are also being used for constructed buildings to track maintenance and equipment performance and even usage patterns of the occupants. The data is uploaded in real time and can be used to aid in increasing the efficiency and performance of future designs. For D&D it can be used to track progress and identify schedule conflicts.

Bringing IoT and BIM technologies to bear on decommissioning will provide the framework for integration of robotic capabilities, data management (such as geostatistical), and project management capabilities that can have meaningful near term benefits on cost and efficiency of decommissioning nuclear facilities. 4D CAD models are starting to be used to design, plan, schedule, and operate construction projects in order to more efficiently plan and manage complex projects where safety hazards [73] and conflicts between work groups have a high potential [74–76]. These technologies are also being applied to planning deconstruction or demolition projects [77]. Électricité De France (EDF) just initiated a Plant Lifecycle Management (PLM) project for new build and existing nuclear facilities that includes BIMs, methodologies, and tools to ensure that construction, inspection, maintenance, and modification requirements are fulfilled [78]. Among all the information related to a power facility, 3D data provides not only the as-designed (CAD) but also the as-built representation of the geometry of the facility components (HVAC (Heating, Ventilation, & Air Conditioning), cable trays, pipes, valves etc.) as well as their relative position. The PLM includes a database on information related to the 3D CAD model [79]. Dassault Systèmes of France is a leader in PLM systems that use 3D CAD models [80]. The goal is to take into account the whole plant lifecycle: engineering, building, operating, maintaining, and decommissioning [78]. Algorithms and computer modeling can be used within these frameworks to determine the most efficient sequences for specific activities [81,82]. RFID tags are being attached to welds to allow all the previous data about the weld, the inspections performed, the results, and the individual who performed the inspection to be read from the tag. This type of data storage and tracking can be used for a lock-out tag out to ensure the locked-out components are the correct ones and that all the items in the plan have been locked out (Fig. 8.7).

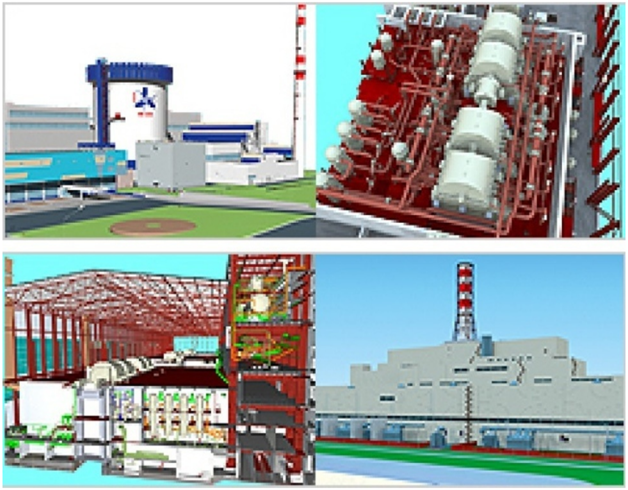

Fig. 8.7 NEOLANT BIM for Nuclear Facilities [83].

8.3.3 Location awareness and pattern recognition

As discussed above in helping to understand the role of the BIM infrastructure, various technologies are available to track position within a 3D CAD model. These include GPS, which is commonly used in outdoor applications such as Kartotrak [84], and data loggers [85] used for surveys as well as autonomous equipment operations like Caterpillar MineStar [59]. Technologies are now available to allow similar tracking inside buildings [86] and at locations where GPS cannot be used. These include Wi-Fi Real Time Location Systems (RTLS) [87], triangulation such as Q-Track's [88] Near Field Electromagnetic Ranging (NFER) products, and also depth perception used by the Google Project Tango tablet [89].

In addition to the IoT, location awareness, static 3D CAD/GIS, and BIM technologies discussed above, there are a couple of other emergent capabilities that should be understood and integrated into the decommissioning. These include dynamic pattern recognition and 3D CAD capabilities, both of which are rapidly developing and key technologies that augment those discussed above especially in a construction or decommissioning environment where the facility and project are constantly changing.

The ability to dynamically update the 3D CAD/GIS BIM is critical for efficient use and deployment of the capabilities discussed in this chapter. Current technologies such as 3D laser scanning are available and currently being used [90]. Russia has developed a BIM system called NEOLANT for nuclear facilities that uses 3D laser scanning [83]. LED-based scanning technologies are being developed as an alternative to laser scanning in order to provide smaller more dynamic 3D CAD imaging systems. [91] Photograph-based 3D CAD modeling capabilities are also available and could facilitate the update of BIM CAD models through video feeds and cameras on equipment such as remotely operated equipment, robots, and aerial drones [92–97]. It has also become feasible to outfit equipment with devices such as a Google Project Tango tablet or Tango enabled smart phones [188] to more precisely update and build 3D CAD environments/objects [98,99]. The tablet can create a 3D CAD model, locate items within the field of view in the 3D CAD models, and identify the position of the item in the 3D CAD model. Thus, a piece of equipment outfitted with a Project Tango tablet knows the position of all the items in the field of view within the 3D CAD BIM and can update the BIM (Fig. 8.8).

Google Project Tango has already integrated use of the tablet into autonomous robotic applications to allow motion tracking, area learning, and depth perception [89]. Pattern recognition and image processing [184,185] coupled with location aware BIM technologies can also be used to automatically track and monitor construction progress and schedule status [101–104]. Remember this capability when we discuss remote sensing technologies such as gamma cameras, alpha cameras, and Laser Induced Breakdown Spectroscopy, where the detected data is linked to objects in the field of view, not the physical location of the instrument in the BIM.

Drone-to-map technologies can be used to fly over sites and create detailed 3D models of current structures and topography. These hold promise for expediting the development of BIMs and for updating them as demolition of structures and remediation activities proceed [105–107]. Aerial site configuration changes can be mapped and tracked using drone-to-map capabilities.

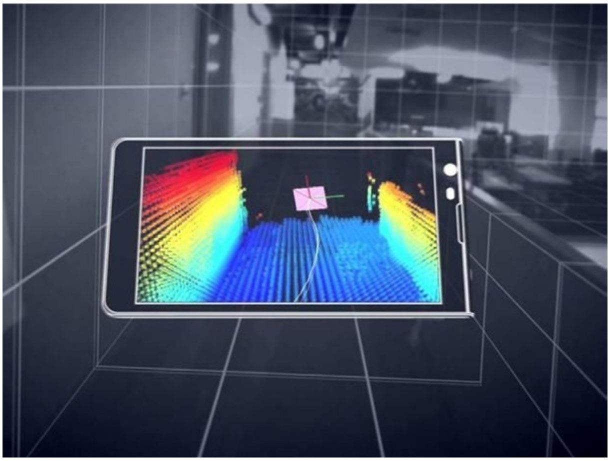

Fig. 8.8 Google Project Tango 3D Mapping Tablet [100].

Thus, there are current technologies that can be brought to bear to update the BIM and track physical and contaminant characterization data within the BIM.

8.4 Characterization and project planning technologies

8.4.1 Role of characterization and project planning

Characterization for decommissioning is often considered too narrowly to only encompass the identification and distribution of contaminants. To construct a valid decommissioning cost estimate, decommissioning, and material handling plan, characterization must also include the physical attributes of the facility and infrastructure. These are often referred to as system, structures, and components (SSCs). Physical characterization allows planning and tracking of structure and components weights, materials, surface areas, volumes, etc. for decommissioning planning and modeling. Contaminants characterization shows concentrations and locations of contaminants for decommissioning planning, waste disposition, end state fate and transport modeling, and demonstration that site release criteria have been met.

Obtaining this information is an iterative process as the decommissioning progresses since the physical state of the facility is dynamic and the access to locations may be prohibited by physical layout and conditions. Drone-to-map capabilities can be used to layout a preliminary BIM of the site. Laser scanning, Google Project Tango tablets, and other rapid mapping capabilities can be used to fill in the details of the site interiors for the BIM. Artificial intelligence pattern recognition software can be used to fill in the structural details of the SSCs using the plant grid within the BIM. Data gaps in the physical and contaminant characterization pose risk and can have serious health and safety and project execution impacts. 3D rendering of the characterization data within the BIM allows those data gaps to be more easily identified. A typical data gap is the location and layout of underground or embedded commodities. Efforts such as those discussed for Exelon's buried commodities initiatives can be used to fill that data gap. The existence and extent of subsurface environmental contamination from leaks and spills is another example of a characterization data gap that greatly impacted the Connecticut Yankee decommissioning. Inadequate characterization of work place contaminants leading to unplanned worker exposures or environmental releases is another example. Tagging available data to the BIM allows these types of data gaps to be identified.

The physical and contaminant characterization information is required to develop the means and methods by which the decommissioning project can be executed. Knowing the identity of the materials, dimensions, thicknesses, and weights of SSCs is necessary to bring the most cost effective removal and material handling means and methods to bear on their removal, packaging, and transport from site and the schedule durations and coordination required to accomplish these activities. The contaminant levels and distribution impact the method by which the SSCs can be removed. Do they pose a personnel exposure hazard that impacts the means and methods and the controls required to safely execute their removal and handling? How will the materials be dispositioned? Do they have value for reuse or as recycled materials and can they be cleared for release from the site? Will they require disposal at specially licensed facilities like radioactive waste landfills, hazardous waste landfills, or require storage on site until disposal options become available? Tagging contaminant levels and distribution data to the BIM allows geostatistical analysis to be used where kriging can identify locations of high and low uncertainty in the information and efforts can be focused on obtaining the data in areas of low certainty to increase the reliability of the data.

All of this characterization information and much more is required to formulate a realistic decommissioning cost estimate and execution plan. In short, the more complete and accurate the characterization is, the more reliable and safe the project planning is.

Emergent technologies discussed in this chapter can improve the accuracy and lower the cost of assembling characterization data by updating the BIM with information gathered in the field and from off-site analysis with the information as it is gathered and reported. Once the BIM is updated all the various disciplines and projects have instant access to the information through their mobile devices.

8.4.2 End state planning and modeling technologies

For a facility undergoing D&D, the project's "end state" is a major determinant of the cost, schedule, and risk [108]. The planned end state configuration is as equally important as the starting physical and contaminant characterization. It must be an initial goal of any project to define the physical and contaminant end state required to meet the decommissioning objectives as early as possible. Development of an end state BIM that encompasses the SSC configuration and the contaminant levels that must be achieved for release is critical for defining a reliable execution plan to transition the site from the current characterization status to the one required to complete the decommissioning. The end state BIM compared to the current decommissioning BIM allows the activities required to achieve end state and the progress made in moving toward that goal to be identified.

Without a good characterization and a clear end state site conceptual model the dismantlement process cannot be efficiently executed and the contaminant characterization and remediation plan cannot be effectively implemented. While leaving the structures for future use in an industrial or residential scenario can minimize the waste and dismantlement challenges it requires more detailed and extensive characterization and evaluation of post decommissioning exposures to future occupants from the remaining SSCs. For SSCS being removed, the characterization is limited to what is required for removal means and methods, material handling, and waste disposition. Those SSCs left in the end state after site release must be evaluated for release criteria and potential future exposures of occupants.

Acceptable contaminant concentrations clearance levels or acceptable future occupant risk levels are typically defined by applicable regulations. However, overall end states are also driven by modeled risks, implementation of the ALARA, or the "how clean is clean enough" principle. In addition to defining an end state that meets regulatory requirements, choosing an end state that is compatible with sustainable economic development often requires negotiation by the facility owners working with regional and national regulators as well as local stakeholders. Some decommissioning scenarios require long-term monitoring of waste storage facilities, site environmental contaminants, or involve monitoring conditions while in SAFSTOR or at partially decommissioned facilities in care and maintenance such as the Magnox reactors.

Maximum post facility release exposures of future occupants to contaminants left in the end state are evaluated up to one thousand years in the future, requiring fate and transport models that are often complex. A conceptual site model that defines the end-state configuration and acceptable contaminant levels is critical for effectively planning decommissioning activities. The conceptual site model is then used as input to fate and transport computer models such as RESRAD, PC Cream, and MODFLOW for postclosure facility use scenarios such as resident farmer agricultural pathways or RESRAD-BUILD for industrial scenarios involving use of site buildings and to assess potential environmental impacts [109].

The most widely used modeling codes in the decommissioning industry in the United States are RESRAD, or RESRAD Offsite for soil areas and back filled basements where the end state is below ground level and there is no future use of site buildings. RESRAD-BUILD or D&D is used for building surfaces left in a residential or industrial future use scenario. Both RESRAD codes were written and are maintained by Argonne National Laboratory. RESRAD-OFFSITE can calculate doses to receptors adjacent to the site as well as those located within it. A geostatistical code ISATIS is used in Europe for fate and transport modeling and risk assessments. Other codes used are COMPLY/CAP-88, PC-CREAM, and DOSDIM or DOSDIM + HYDRUS [110].

In the United States, end state modeling has applied soil derived concentration guidelines (DCGLs) in pCi/g intended for surficial contamination (e.g., 15 cm) to subsurface contaminants exposed during excavations and building surface DCGLs (in pCi/m^2) intended for building occupants to end state basements that will be back filled and covered in the end state. Excavations that were backfilled and building surfaces that were backfilled were released using surface DCGLs. These were unnecessarily restrictive because both DCGLs have direct radiation and airborne radioactivity pathways that are not applicable to subsurface contaminants. This has evolved to more complicated modeling that assesses groundwater concentrations and pathways from the subsurface release and transport of the radionuclides as well as scenarios like home construction where basements are in closer proximity to contaminants or excavation and well drilling scenarios where contaminants are brought to the surface. Potential doses from the end-state configuration and pathways are evaluated to define the acceptable source terms and radiological and hazardous contaminant levels that can remain.

For subsurface end-state contaminants such as building basements that can release contaminants to groundwater over time, additional programs such as Brookhaven National Laboratory's DUST MS may be required to calculate peak groundwater concentrations and concentrations on the soils and fill material below the water table in order to input groundwater peak concentrations into the fate and transport model for evaluation of future doses or contaminant levels. This often includes alternate scenarios such as well drilling, home building, and excavation that can place future residents near or in contact with contaminated material [111]. Hydrogeological modeling programs such as MODFLOW, used to model the transport of radionuclides in groundwater to off-site locations, may also be required to assess the potential environmental impacts of the end state [112].

Once the end state exposure scenario(s) is chosen, the contaminants of concern must be identified, and the model parameters need to be decided upon and input. These parameters include location, area, and depth of contamination remaining in soils or on structures; the hydrogeological parameters of the site; fate and transport parameters, such as depth to water table, site geology, porosity, hydraulic conductivity; and distribution coefficients (K_{ds}) of site soils and fill materials. This requires identification of the critical parameters in the site conceptual model and hydrogeological characterization to be included as part of the physical characterization to develop accurate fate and transport and exposure assessment models. The end use and critical member of the population must also be defined to evaluate exposure pathways and exposure durations, rates, and dose conversion factors.

Typically, these fate and transport codes allow probabilistic analysis of the model to be run with each input parameter assigned a statistical distribution around a mean and standard deviation. The code picks random values from within the distribution and runs the model using them to determine which parameters significantly alter the outcome of the dose or risk assigned. Often this process is underpinned by processes such as Latin hypercube sampling to ensure that values chosen randomly are representative of the entire distribution of possible values and have not been grouped by chance at one particular part of the distribution. This allows characterization of the sensitive parameters like distribution coefficients K_{ds} to be focused on where other parameters like root depth may have no impact on exposures in subsurface end states.

Input parameters that significantly alter the outcome are called "sensitive parameters" and either require further site-specific justifications for the values chosen from literature or site samples or are chosen from the upper or lower quartile of the distribution to ensure that the modeled doses or risks are conservative. The probabilistic analysis must be performed for each contaminant of concern and the models typically calculate the fate and transport and resultant dose from the daughter radionuclides as well. Consequently, even relatively simple contaminated zone and hydrogeological models require long computer run times on conventional personal computers to perform probabilistic analysis on radionuclides, such and ^{239}Pu or ^{241}Am and their many daughters. At sites contaminated with nonradiological contaminants such as heavy metals, asbestos, or PCBs, the fate transport and risk from residual levels of these contaminants must also be considered when determining acceptable end-state criteria based on the “combined risk” from radiological and non-radiological contaminants.

Thus, physical characterization and contaminant characterization as well as an end state site conceptual model drive the characterization process that is aimed at filling data gaps in both models. The technologies discussed in this chapter can improve the accuracy of the characterization, identify data gaps, and provide more cost effective and accurate characterizations by using BIMs and technologies that upload characterization data from the field, drawings, and lab analyses to the BIM.

8.4.3 Geostatistics

Current sample planning and acceptance criteria in MARSSIM, MARSAME, and EURSSEM are based upon statistics that assume a uniform distribution of contaminants within the survey area. Unless contaminants were introduced from an inundation or airborne event this is rarely the case. The levels and locations of contaminants vary widely at contaminated sites undergoing decommissioning within the SSCs and the site environs. Geostatistical software applications use actual characterization results without an assumption on their distribution. They have been developed and are being used to produce 2D and 3D maps of contaminant distributions within an area of interest. Adoption of geostatistics and current use is largely confined to France and Europe with some uses by the Environmental Protection Agency (EPA) and Department of Energy (DOE) in the United States. They are not a recognized method in the Nuclear Regulatory Commission’s (NRC) MARSSIM-based guidance. However, they have been approved for use in clearance of subsurface contamination in an NRC NUREG. Class 1 areas are areas that have had or are likely to have had levels exceeding the clearance DCGLs. Due to the presumption of uniform distribution, Class 1 areas are required to have a 100% scan of the survey unit to demonstrate the release criteria has been met.

In geostatistical modeling contaminant and physical characterization data, such as contaminant concentrations on structures, soils, or in the groundwater, is tagged spatially to a 2D or 3D CAD model with x,y,z,t coordinates. This allows the contaminant distributions to be mapped and visually displayed [174]. The uncertainties of the measurement are often included. Algorithms are then used to interpolate the concentrations between characterization data points in the model to estimate the distribution of the contaminants at locations between sample points. Geostatistics was developed and used for the mining, oil, and gas industries to provide 3D representations of potential reserves based upon investigative well drilling data and site geology. These applications provide statistical confidence levels and uncertainties associated with the distribution of the asset within the 2D or 3D grid. The oil, gas, and mining models are created using the physical characterization data available about the site geology. It is supplemented with asset characterization data from test wells or shafts. Drilling a test well or installing test shaft is expensive and the oil, gas, and mining industries used geostatistical capabilities to only drill at locations where the probability was high based on site geology and known asset distributions at other locations. Additional test wells were then targeted at locations where uncertainty was high and only enough wells drilled to achieve high confidence level in the accuracy of the reserves model. The power of geostatistics is not in making pretty maps, but it is in using the data to identify data gaps in the characterization data that carry the risk of high uncertainty and in targeting only the locations and only the numbers of samples required to fill those data gaps and achieve the desired confidence (e.g., typically 95%) in the model.

In decommissioning applications, available sample and survey data is entered into the software, including the location coordinates and contaminant levels or concentrations and measurement statistics such as the standard error of the result. Most geostatic software packages support uploading of this data from standard CAD file formats and from spreadsheet files of the sample data that include the grid coordinates. This process can be greatly streamlined by using the location aware technologies previously described for outdoor areas where GPS coordinates are transmitted from the field along with the measurement data. The process can be further streamlined by using BIMs and the location aware technologies previously described. The geostatistical software uses the available known data to interpolate contaminant concentrations at grid locations between input data points by a process known as kriging. Most include selection of several kriging algorithms for interpolation of the data. The results are displayed as maps that show the likely contaminant distributions and statistical confidence levels and uncertainty associated with the data. This has brought the predictive and sample minimization capabilities of geostastics to bear on the decommissioning characterization and site release characterization efforts on the projects that have adopted this technology.

For instance, in the decommissioning world, areas where concentrations are relatively uniform require minimal sampling to develop models that have high certainty of their distribution and the MARSSIM-based statistics allow less than 100% scan at locations where the probability of exceeding a DCGL is less likely. But in survey units where one or a few locations exceeded the DCGL, a 100% scan is required. How much data, and at what locations, is enough to achieve a 95% confidence that the characterization data is sufficient to plan the decommissioning or to demonstrate that the site criteria has been met at such locations without doing a 100% scan? Geostatistics' predictive capabilities show where and how many additional characterization data is required to achieve 95% confidence without 100% coverage. After all, 100% coverage of subsurface contaminants is what we in the United States refer to as "remediation by sampling."

A geostatistical framework is a sound data processing technique and an efficient way to optimize the sampling strategy for the initial radiological and nonradiological characterization of concrete structures and soils [113–116]. Historical Site Assessment (HSA) data, core sample data, and surface scan data have been integrated into geostatistical models in order to map concrete structure contaminant concentrations and determine waste classification levels [113,117]. They have also been used for shallow and deep subsurface soil contaminations using historical data, sample gamma scan results, and coring data to optimize sampling and evaluate various remediation scenarios, costs, and risks [115,113,186,187]. Comparisons of estimated versus actual contaminated soil removal volumes have shown that geostatistical modeling tended to underestimate the soil volume removed by 10% to 30% [114]. It should be noted that estimates of soil volumes requiring remediation are typically low due to the excavation process itself, which often requires ramping, sloping, and results in cross contamination of some clean soil during the remediation process. The technique has been used to identify areas where the confidence interval is too large and additional sampling is required [114,113,118].

A full-scale field experiment applying 4D (3D time-lapse) cross-borehole Electrical Resistivity Tomography (ERT) to the monitoring of simulated subsurface leakage was undertaken at a legacy nuclear waste silo at the Sellafield Site, UK. The study found that this type of geophysical imaging has the potential to provide the detailed spatial and temporal information at the (sub-)meter scale needed to reduce the uncertainty in models of subsurface processes at nuclear sites [119].

Geostatistical calculated cartographies have been successfully performed using ISATIS software [115]. Specialized vehicles outfitted with scanning instrumentation have been developed for surface mapping contaminated areas using geostatistical software like Kartotrak in France [120]. Cartographies created through kriging capture the spatial concentrations of the contaminant and, per measurements points, predict a likely value on each map point while also quantifying the associated uncertainty. Kartotrak.one software is a new, easy-to-use, and fast application for thorough data quality control and accurate contamination mapping. Kartotrak.one is a light version of Kartotrak. The software gathers Kartotrak exploratory data analysis and rapid mapping functionalities [84].

Geostatistical software that integrates with MARSSIM is also available. University of Tennessee Knoxville has developed free software the Spatial Analysis and Decision Assistance (SADA) that includes 3D geostatistical capabilities for subsurface modeling to aid MARSSIM planning and surveys for final site clearance. SADA provides several critical MARSSIM tools for sample design and checks for compliance. These include a formal MARSSIM approach for individuals building a MARSSIM assessment from scratch. In addition, users can access various stages (available through the MARSSIM Quick tools) of the process to introduce a SADA mid-evaluation. Regulators can also use the quick tools to check a licensee's work [121].

Decommissioning projects need to move away from MARSSIM entirely and adopt geostatistics in order optimize characterization and site release [194]. Contaminants are not uniformly distributed in the real world. Geostatistics limits the sampling and surveying required to the amount required to achieve the desired confidence level. With the use of 3D CAD Building Information Models and wireless data transfer with spacial recognition networks, geostatistical tools such as these are ready to deliver increased efficiencies in site characterization, remediation, and clearance. These efficiencies can be further optimized by adopting the in situ characterization technologies discussed in the following section.

8.4.4 3D gamma camera

REACT Engineering Ltd has made improvements to further develop its NVisageTM camera and software system [122]. The NVisageTM software system takes laser scanning and gamma camera radiation data from a building and constructs a 3D map of where the radioactive sources are potentially located within the building [123]. Current NVisage systems [124] have created cameras small enough to access tight areas and able to deliver detailed mapping. The 116 mm-diameter gamma camera weighs less than 10 kg. Its small size means it can access most areas within plants and its lightness offers greater maneuverability (Fig. 8.9).

The system uses a slot rather than a long cylinder to scan a full sphere of the gamma spectrum. Combining this with a laser scanner or photogrammetry technology creates a 3D model of the area and point cloud map of gamma levels. The camera can build up a 3D full picture of the radiation level in the areas of interest. Complementing the camera is patented modeling software that takes dose readings from multiple locations within a specified area and then applies physics-based calculations to identify the lowest dose area from which to start out. It then identifies hot spots and the system can calculate radiation levels if different methods of shielding are applied or radioactive materials are removed. This enables cost and benefit analysis of alternative decommissioning methods. The system has been used at Sellafield in the United Kingdom.

Fig. 8.9 NVisage reduced size 3D gamma camera [124].

Engineers at the Fukushima plant in Japan are using UK company Createc's N-Visage camera and imaging system to model radiation in 3D [124] (Fig. 8.10).

At Sellafield, Createc's N-Visage system was used to laser scan, gamma image, and obtain spectroscopic data for a representative radio active cell. An accurate model of the cell and its contents was generated with a radiological map highlighting radiation hotspots. The N-Visage predictive gamma modelling software produced a 3D model of the activity distribution. The newly acquired data was used to challenge the assumptions in the decommissioning mandate. It confirmed the manual decommissioning scheme is appropriate but that aggressive decontamination is required to achieve an 80:20 ratio of low to intermediate level waste [125] (Fig. 8.11).

The small size also enables a new capability for a radiation mapping drone that is capable of flying indoors autonomously, or with very little human input, and constructing a 3D map of radiation levels. Createc has combined its expertise in navigation and radiation mapping with Blue Bear's experience of Unmanned Aerial System (UAS) and SNAP Avionics to create an autonomous drone 3D gamma camera [122]. This has been described as "a fairly significant step towards a robotic radiation survey capability. It's able to act on its own or make its own proposals to be validated by a user in real time based on an understanding of the physics. It's quite a unique thing" [124]. The indoor trials at Sellafield of the Remote Intelligent Survey Equipment for Radiation (RISER) demonstrated the capability of radiation mapping and imaging within a GPS-denied environment. RISER, developed in partnership with Createc and Blue Bear Systems Research, utilized Simultaneous Localization and Mapping algorithms to localize itself and produced radiation maps of Cells 1 and 4 in the Solvent Recovery Plant. The trials provide a proof of-concept and future deployments will produce radiation maps that can be used in decommissioning planning. Further trials are planned to radiologically map the Pile Chimney.

Thus, this technology has the capability to create the interior 3D CAD for the BIM while at the same time characterizing the radiation field and evaluating source removal and shield options. If it is outfitted with an actual RFID within an RTLS system, the

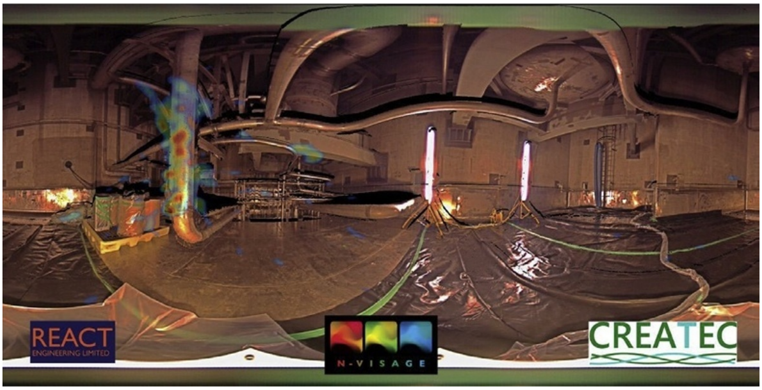

Fig. 8.10 3D CAD and radiation fields of Sellafield medium active cell created with NVisage [125].

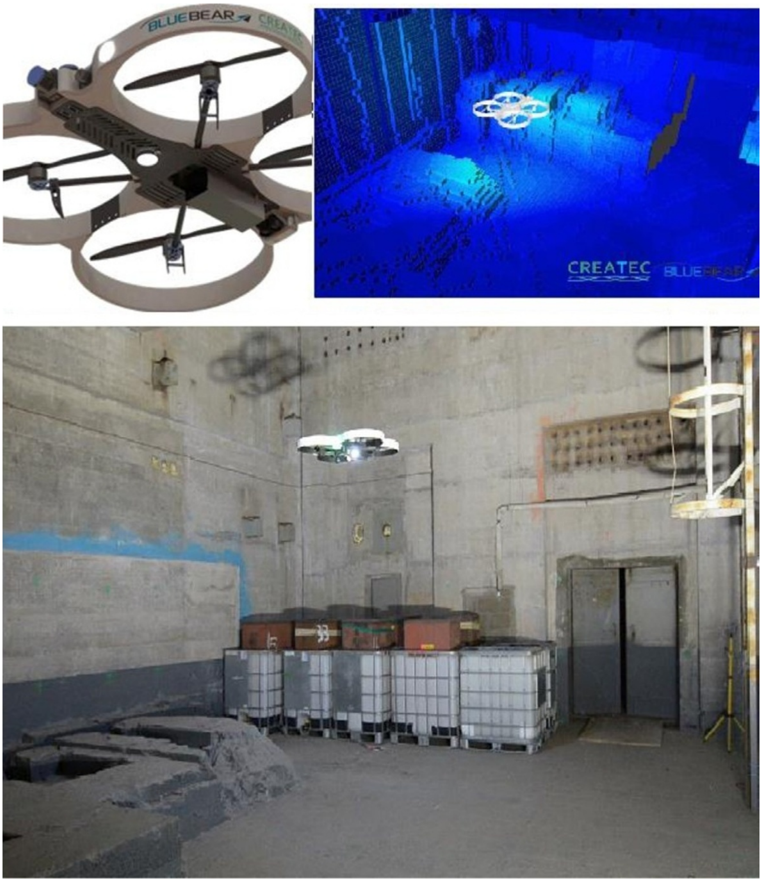

Fig. 8.11 RISER NVisage 3D gamma camera on blue bear autonomous drone [126,125].

position is known within the BIM and the 3D CAD model created of the SSCs and point cloud radiation fields can be synchronized with the BIM. This is a valuable tool for initial physical and contaminant site characterization and for updating the BIM as sources and SSCs are removed (Fig. 8.12).

Similar drone-to-map capabilities combined with radiation detection are being developed at Sellafield. The outdoor trials using ImiTec's Autonomous Airborne Radiation Monitoring (AARM) system demonstrated a world first in UAS low level radiation mapping. AARM was used to radiologically map three areas of the Sellafield site; a legacy contaminated area, some uranium-containing isofreights, and the Multi-Element Bottle store. The trials demonstrated the system's capability in large-scale radiological mapping. With the continuing development of lightweight sensors, the opportunities for UAS deployment are increasing and could be the most cost-effective solution for a range of operations such as asset inspection (both indoor and outdoor), public relations photography, and emergency response operations [125].

Fig. 8.12 ImiTec Autonomous Drone Outdoor Radiation Mapping at Sellafield [125].

8.4.5 Concrete depth profiling

Concrete in structures where radioactive liquids have leaked or spilled can become contaminated to different depths with radionuclides sorbed into the concrete. In order to plan the disposition of concrete removed, the remediation required to achieve end state, inform the end state conceptual site model, and predict the fate and transport of radionuclides after site closure it is necessary to determine the contaminant depth profile in impacted structures. Currently this is an arduous process requiring multiple solid cores which are then sectioned into slices or drilling with concrete dust sample collection at each depth to create a depth profile when the slices or samples are analyzed.

Usually sample locations are targeted at hotspot locations to ensure there is sufficient activity in the samples to get a good fingerprint or radionuclide mix that is indicative of the true ratios of gamma emitting to non-gamma emitting radionuclides. Otherwise the detection thresholds or minimum detected concentrations (MDCs) are too high relative to the gamma emitting nuclide concentrations. Based upon a limited number of cores (e.g., 20 or less) and off-site analysis of some samples (e.g., 10 or less) a depth profile is constructed and extrapolated to the entire area. Cracks in the concrete can further complicate this process (Fig. 8.13).

Obtaining concrete profiles is time consuming and requires manually transposing core locations and depth profile results to the BIM or 2D maps of the area and spreadsheets or databases. The process is susceptible to transposition errors (Fig. 8.14).

At most nuclear facilities, the predominant nuclide sorbed is Cs-137. This is because the activity is accumulated over many years resulting in lower levels of shorter half-life nuclides like Co-60 and because Cs-137 and Sr-90 are more mobile in concrete. At Zion, 73% of the total source term, including non-gamma emitters, was Cs-137 and 78% of the source term was in the first 5 cm of concrete. Although concentrations vary this type of Cs-137 dominated profile is consistent with other reactors. For activated concrete, the gamma emitter Eu-152 becomes the dominant nuclide and peak concentrations are several inches in where the thermalized neutrons peak.

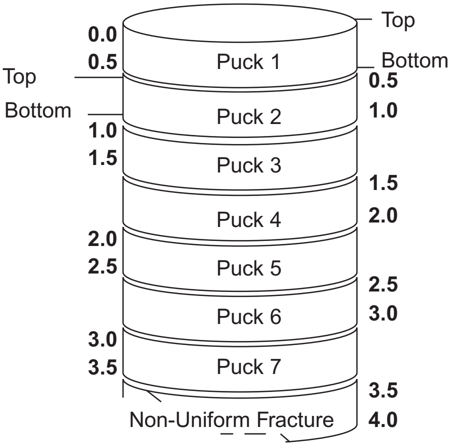

Fig. 8.13 Core sample puck labeling.

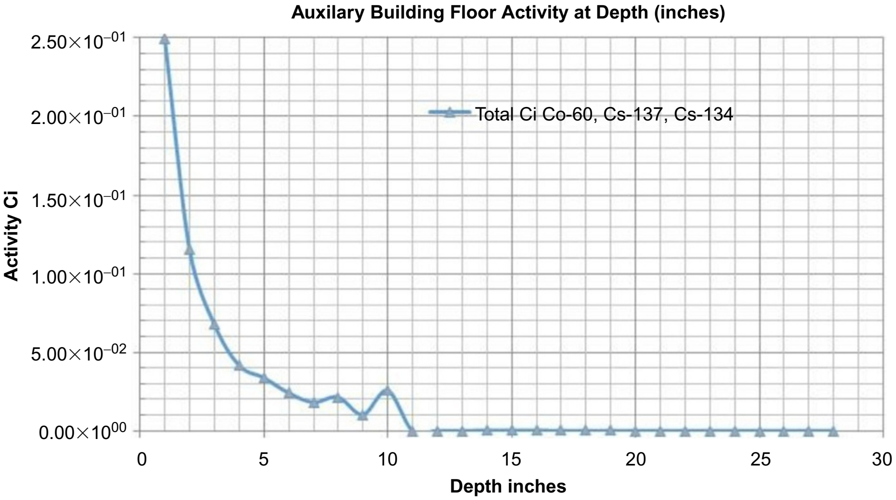

Fig. 8.14 Zion auxiliary building activity profile at depth

At Sellafield technology is being developed to nondestructively evaluate the contamination in concrete. Detectors measure the gamma radiation spectra from the concrete structure and through its interrogation and modeling can determine the contamination depth profile. Trials of three systems from Createc, Cavendish Nuclear, and Canberra and Areva were carried out in the first generation reprocessing plant. Results will be verified against core samples taken in 2015/16 [125]. If these devices are proven, they can be tagged with an active RFID in an RTLS systems and the data can be loaded to the BIM from the field, greatly improving the accuracy and efficiency with which impacted concrete can be characterized. Decommissioning managers should actively await the results (Fig. 8.15).

Fig. 8.15 Example of concrete profiling equipment setup undergoing testing at Sellafield [125].

8.4.6 Small diameter flexible and insertable fiber optic gamma spectroscopy

Pipe inspections and other difficult to assay locations may benefit from an advancement in the gamma isotopic capabilities using fiber optics and sodium iodide detectors with multichannel analyzer capabilities. Traditionally, NaI detectors are used to measure surface contamination in piping by calibrating the detector to a source of the same diameter as the interior of the pipe. Sampling must be performed to determine the radionuclide mix or fingerprint. Conventional NaI pipe inspections are gross gamma detectors without isotopic identification capabilities. The ratio of a readily detectable activation product such as Co-60 to hard-to-detect activation radionuclides such as Fe-55, Ni-59, Ni-63, etc. are used to infer their concentration from the Co-60 results. Development of small (3 × 3 mm) flexible and insertable fiber-optic radiation sensors for gamma spectroscopy will enable characterization of embedded piping such as floor drains and piping from sumps [127] (Fig. 8.16).

8.4.7 Alpha camera

Alpha cameras use ultraviolet emissions from nitrogen in air fluorescence caused by alpha particles to image surface deposits of alpha emitters. Alpha imaging is feasible under certain lighting conditions using the UV fluorescence in air that results from alpha particles interacting with air [128–131]. Currently these systems are capable of detecting 40 $\mathrm{Bq/cm^2}$ with a 1-hour exposure and 100 $\mathrm{Bq/cm^2}$ when using a 10-min

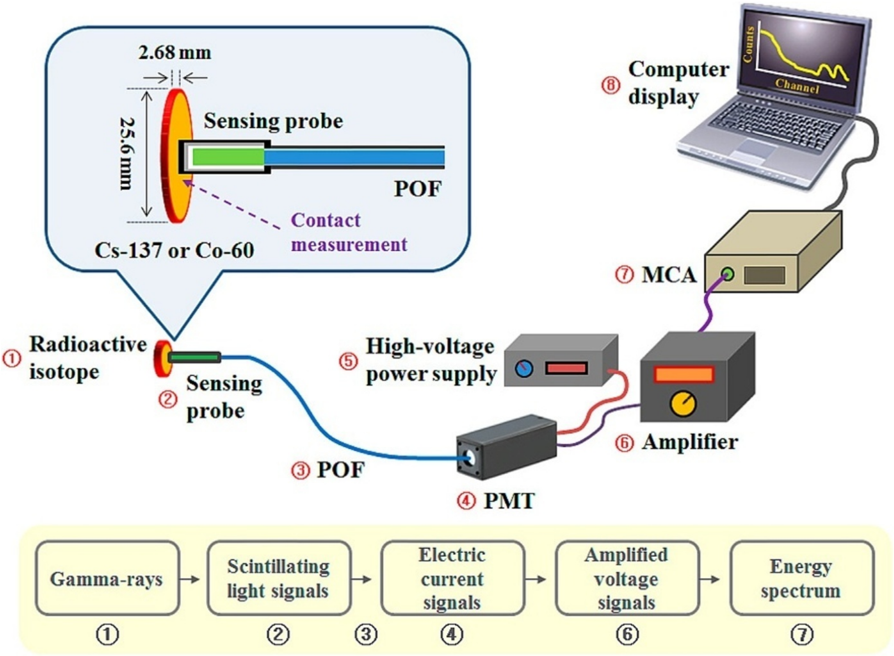

Fig. 8.16 Small flexible remote gamma spectroscopy system [127].

imaging time [132]. This equals 167 dpm/100 cm^2, which makes them marginally feasible at present for identifying locations with high alpha surface contamination that pose a high airborne radioactivity risk. It would take a long time to do a thorough imaging of a room or area with these sensitivities and imaging times. But if the device was outfitted on an autonomous or semi-autonomous robot with active RTLS and a 3D CAD imaging system like a Google Project Tango tablet, it might be feasible to methodically image plant areas at high alpha contamination risk and upload the data to the BIM since the Google Project Tango 3D CAD of the wall, floor, or object being imaged could provide the *x*,*y*,*z*,*t* coordinates of the images.

Connecticut Yankee had high alpha contamination levels in the areas that were an order of magnitude to two orders of magnitude higher than the 10-min sensitivity. This is a particularly difficult problem for decommissioning because the high levels are sporadic and confined to areas not decontaminated or that were leaked on when high alpha concentrations were present in reactor coolant from fuel leaks. An annual limit of intake can be obtained from an inhalation of a few thousand dpm and the chances of finding all the locations of high contamination based on smears surveys is minimal. Thus, alpha cameras could be a valuable tool identifying locations with hazardous surface contamination levels for remediation.

There are also possibilities that the detection threshold could be lowered as UV cameras become more sensitive and by using lasers to increase the UV emissions from the nitrogen in an excited state in the air. Technologies such as pulsed lasers tuned to excite ionized atoms could increase the signal from ionized air above the contamination. A patent filed for such a device states that Nitrogen comprises approximately 78% of air but only 0.5% of the Nitrogen ions generated by radiation create light naturally [133]. So, ionizing radiation creates 200 times more nitrogen ions than those that fluoresce naturally. If the nonfluorescing ions remain in such a state, 95.5% of nitrogen ions will go undetected, thereby inhibiting the accurate measurement of ionization. A LIDAR system uses a pulsed laser at a wavelength absorbed by ionized nitrogen to increase the UV output [133]. LIDAR technology is an optical remote sensing technology that measures properties of scattered light in air. LIDAR technology can be used from a safe distance to measure ionization resulting from alpha and beta particles as well as gamma rays. The patented LIDAR system employs a pulsed laser transmitter, a telescope receiver, and associated control and acquisition systems. Pulsed light propagates out from the laser transmitter and is directed into the volume surrounding the radioactive source, or the "ion cloud." The ion cloud absorbs the transmitted light. This absorption induces otherwise undetectable, non-fluorescing ions to fluoresce. Light from the ion cloud is then backscattered and the telescope receiver subsequently collects the photons from the backscattered light. The intensity of the fluorescence (determined by the photon count) is measured. This provides an indication of the density of the ionized atoms and source strength. Thus, this is a technology that can have value at high alpha contamination facilities such as fuel reprocessing plants and that has the potential to achieve sensitivities that could reduce imaging times while achieving lower sensitivities in the future.

8.4.8 Laser induced breakdown spectroscopy back packs for in situ heavy metal assay

Laser induced breakdown spectroscopy (LIBS) focuses a laser on an object or sample creating a high temperature plasma of ions that expands with the atoms electrons in an excited state. Light emissions given off when the excited electrons collapse to ground state can be used to identify the elements present in much the same way that flame emission and atomic absorption spectrophotometry is used in the lab to detect low concentrations of elements such as heavy metals. Unlike laboratory instruments that require sample preparation LIBS can be used on materials in any form. Lightweight, highly portable LIBS are available for many applications including dirty bomb response [134] (Fig. 8.17).

Elemental analysis sensitivities in the parts-per-million and parts-per-picogram levels are achievable from manufacturers [135,136]. Any type of material can be analyzed: metallic or dielectric solid, liquid, aerosol, or gases, without any need of preparation. Most of the chemical elements, even the light ones such as hydrogen, can be analyzed with detection limits of few ppms (parts per million) [137]. CEA has developed a handheld LIBS that has already been used for some applications. Tests were carried out in the uranium manufacturing facility (CEA Cadarache, ATUE) during decommissioning of the building to determine uranium contamination fixed on the surface of the walls. The LIBS system was also used to characterize on site the nature of alloys constituting various parts of UF6 containers, providing an instant response to the operator [138] (Fig. 8.18).

Sellafield is developing in situ sludge analysis with LIBS for legacy facilities that have complex chemical and radiological fingerprints.

Fig. 8.17 BOOSTER project use of portable LIBS for radioactive material exposure response [134].

A custom designed and built LIBS system from Applied Photonics Ltd was successfully used to analyze challenging sludge simulants in laboratory conditions. Future trials will test the LIBS system underwater before it is deployed on an active plant [125] (Fig. 8.19).

There is a very strong potential for LIBS to be used for analysis of heavy metals in paints and other materials that could avoid difficult sampling and analysis campaigns required at decommissioning facilities.

8.4.9 3D CAD and BIM optioneering technologies

Building Information Model software packages are now being used in nuclear power construction, operations, and decommissioning. These software packages provide detailed 4D rendering that show the 3D model over a time interval. Information such as document control, project communications, BIM, and mobile field capabilities automate and better control the construction management process [139]. Geospatial data about the site can also include the tracking of hazardous materials and location of assets that have reclamation value as wells quantities and locations of SSCs. The detailed knowledge of the materials and construction can be used to plan the removal

Fig. 8.18 CEA LIBS prototype testing at uranium manufacturing facility [125].

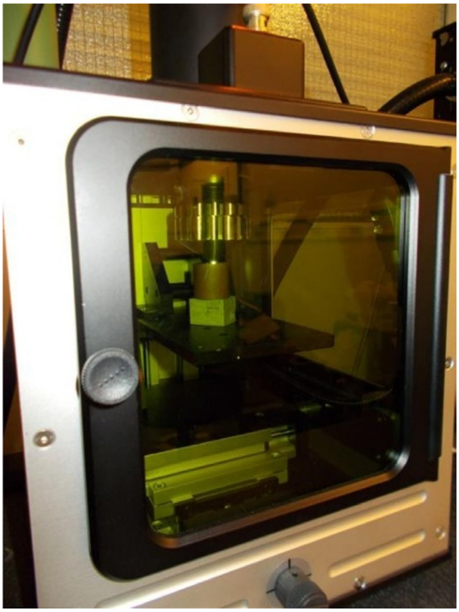

Fig.8.19 Sellafield in situ LIBS sludge analysis.

and packaging of the materials with the 3D CAD model and to evaluate options and identify conflicts in the planned use of equipment and laydown areas.

8.4.10 Probabilistic project planning and scheduling technologies

Probabilistic dose assessment has been used for many years to assess sensitive parameters in end state user fate and transport models that demonstrate compliance with license termination dose criteria [140,141]. Probabilistic risk assessment (PRA) has also been used for evaluating the safety significance of nuclear power plant SSCs and activities for construction, operation, and decommissioning of nuclear power plants [142].

Decommissioning planning and execution is also subject to uncertainties that range from regulatory changes, discovery of unintended site conditions, labor-relations changes, stakeholder constraints, waste disposal cost changes, and many others. Each of the major uncertain variables that contribute to cost or schedule can be evaluated in terms of probability of occurrence, minimum, most likely, and maximum impacts. These estimates can be used to calculate a probabilistic range of costs and schedule impacts using Monte Carlo simulation techniques. Three of these tools—one for cost impacts, one schedule impact, and another for risk registry management—are currently being used to manage risks for a large nuclear power plant (NPP) decommissioning project in the United States. These tools have been developed by VOSE software, headquartered in Belgium.

For the cost uncertainty analysis, ModelRisk is being used. This is an Excel add-on that allows the assignment of statistical distribution multiple input variables resulting in multiple output variables assessed through representative Monte Carlo sampling. For decommissioning applications, most of the statistical distributions used include the Triangle, PERT, and Bernoulli despite the very large number of options available in ModelRisk.

ModelRisk has been used to evaluate decommissioning risk analysis in terms of cost uncertainty. In this analysis, the major cost-risk items have been individually identified. For each of these major items, a cost range is identified in terms of its minimum, most likely, and maximum values and the total number of items is generally between 10 and 30. Once identified, and with concurrence within a project team, these are analyzed within ModelRisk by Monte Carlo sampling. The output options from ModelRisk allow the user to output a cost probability distribution along with tornado plots and spider plots that assist decision makers in identifying the most sensitive parameters that influence the overall cost as seen in Figs. 8.18 through 8.20.

For schedule analysis, Vose Software has created Tamara. This tool is focused on determining a probabilistic schedule analysis given a deterministic schedule (from MS Project or Primavera) and a population of schedule risks and work uncertainties (productivity uncertainty) at a task level. The tool allows the importing of a project schedule developed in Microsoft Project or Primavera scheduling tools. Once imported, Tamara allows the user to identify, create, and assign any number of schedule risks to each line-item of a schedule or to each category of schedule items. Once assigned,

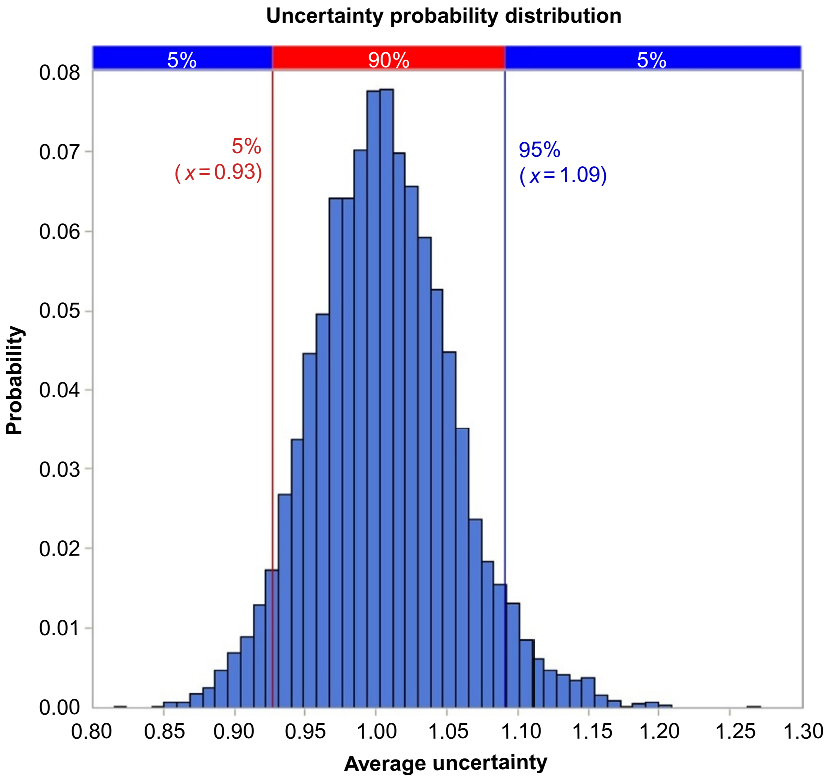

Fig. 8.20 Example uncertainty histogram distribution.

Tamara propagates a probabilistic schedule that allows decommissioning planners to identify areas of high risk or uncertainty in the D&D schedule. The simulation results from Tamara can also be linked to ModelRisk so that one can produce a cost or financial model that accounts for the schedule risks and uncertainty.

The schedule uncertainty propagation is generally applied as a modified PERT distribution and recognizes the differences between tasks performed in series versus parallel. Tamara can work with schedules of tens of thousands of tasks, and it has a unique method for accounting for correlation between task durations that is common for large projects. The Tamara output includes a variety of decision-making tools such as probability distributions of schedule completion, tornado plots, tabular schedule item details, and others. A sample D&D schedule will be highlighted to demonstrate the ease and utility of Tamara in decommissioning and other projects important to our industry.

Examples of Tamara reports are shown in Figs. 8.21 and 8.22.

For managing risks, a risk dashboard database application has been developed that allows risks to be defined with their associated consequences, controls, and mitigations. This new Vose commercial software product is designed to store and manage a site's risk register. It allows risks to be exported into Tamara for inclusion into schedule activities (Figs. 8.23 and 8.24).

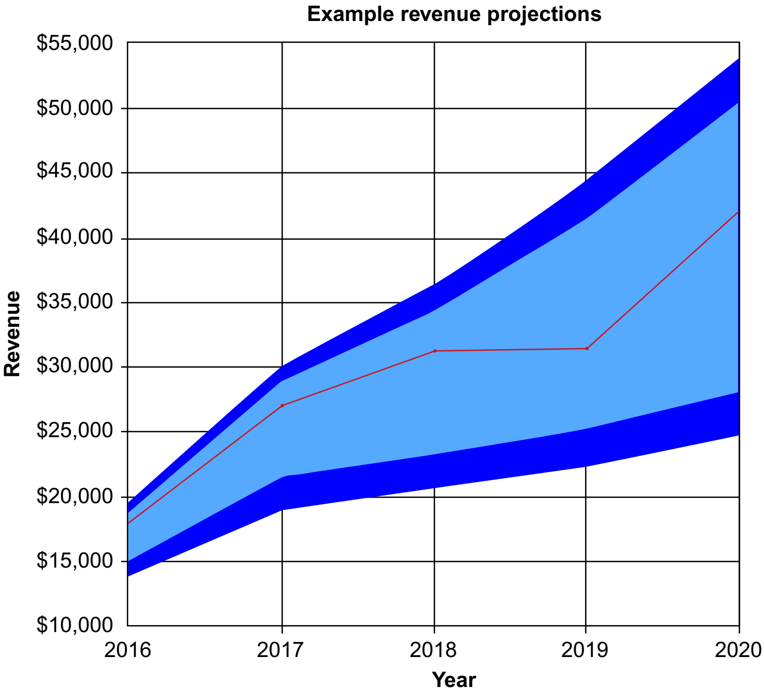

Fig. 8.21 Example trend plot projection.

The risk dashboard interfaces seamlessly with Tamara to assign risk consequences easily to a project schedule. Risks are defined and quantified, along with their drivers and consequences. Within this tool, risks are classified in the following general categories:

- Health Impact
- Schedule Delay
- Cost Impact
- Reputation

In addition to these categories, individual control and mitigating mechanisms can be applied to reduce the probability and impact of risk consequences. The risk register application presents each risk in the form of a bowtie diagram, providing an intuitive display that both illustrates whether the chosen risk management approach is fully implemented and the thinking behind the strategy. An example of a simple bowtie diagram is shown in Fig. 8.23 (Fig. 8.25).

This tool includes a database that allows multiple users to contribute to the risk register and it allows importing of the database directly into Tamara.

These probabilistic tools are well suited for any large or small project including operating NPP, refueling outages, and others. The proper use of these tools will help project managers to understand uncertainties associated with project implementation and to inform managers where resources could be applied to mitigate both schedule

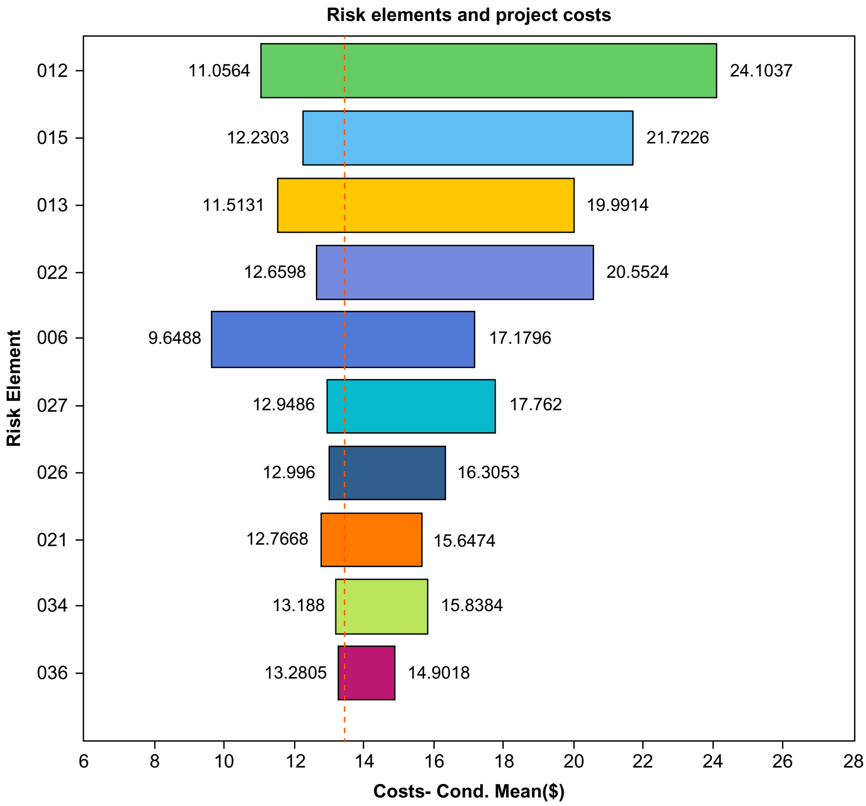

Fig. 8.22 Example tornado plot for risk analysis.

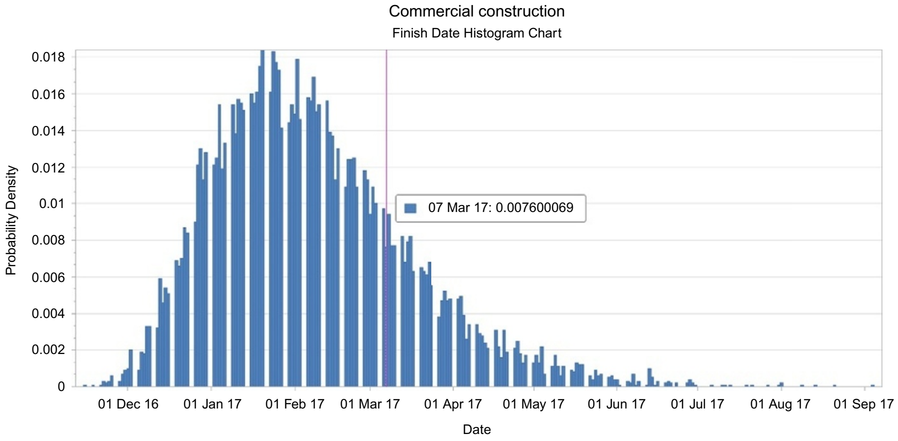

Fig. 8.23 Example schedule uncertainty from Tamara.

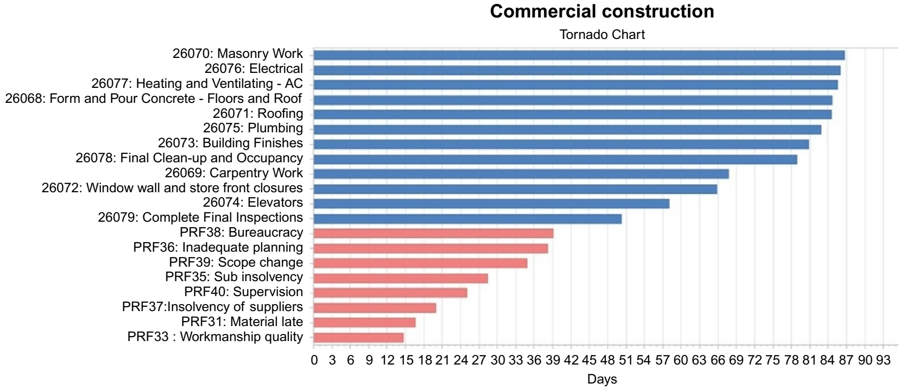

Fig. 8.24 Example tornado plot from Tamara showing driving tasks (*Blue*) and risk events (*Red*).

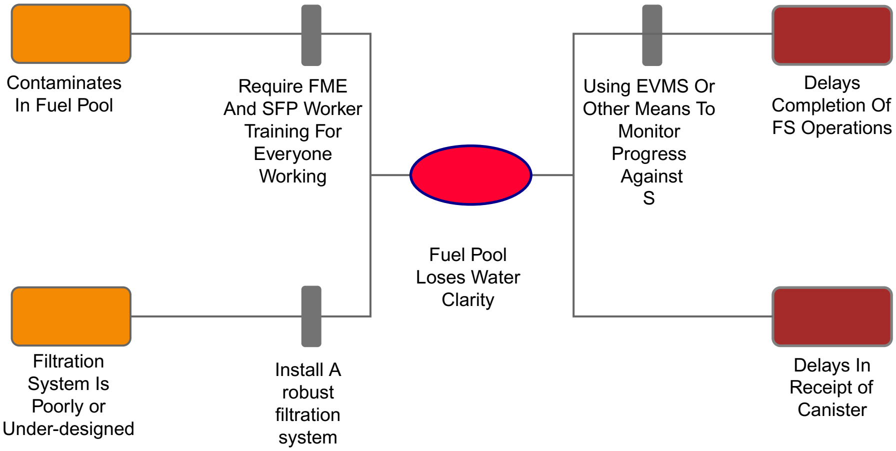

Fig. 8.25 Risk dashboard view of an example risk showing the risk, consequences, control, and mitigating mechanisms.

and cost risks. These applications promise to be important tools in managing D&D cost and schedule, and these same principles can be extended to construction and operation of large projects such as nuclear power plants. The risk analysis tools developed by Vose represents a comprehensive suite of Monte Carlo analysis methods that integrate together and allow for the analysis of project costs and schedule uncertainties as well as the management of risks and mitigation strategies for both large and small projects. These tools have been deployed for a large NPP decommissioning project and will help inform the decommissioning management team of the significant risks along with the ability to actively manage risks and consequences throughout this project. It also feasible to bring probabilistic analysis capabilities to bear on decommissioning cost estimates.

8.5 Dismantling and demolition technologies

8.5.1 Open air laser cutting

The United Kingdom has been aggressively pursuing the development of high-powered lasers for nuclear decommissioning cutting operations. Large power compact 1µm lasers that use optical fibers have made laser cutting for decommissioning feasible. Delivery of the cutting beam through optical fibers allows the expensive part of the equipment to be located outside contaminated areas [143]. Another key factor is the nozzle-tip-to-plate-surface distance (stand-off distance), which has to be kept small and constant as the cutting head moves. Height sense systems for control of the nozzle tip have been developed, allowing robotically deployed laser cutting systems to be used. Laser cutting capabilities have also been tested cutting thick (40 and 100 mm) C-Mn steel bar and plate material using high-powered lasers that have greater tolerances for stand-off distance for applications in which the processing must be done completely remotely and where the exact position/size of the component is unknown [143]. This has also allowed development of hand-held laser guns.

These lasers have been used for commodity removals such as pipe cutting and for development of robotic assembly line material cutting and sizing. Skips used to store Magnox fuel in the spent fuel pools (i.e., ponds) are being decontaminated and recycled to form the containers for storage of high-level wastes on site, during the SAFSTOR care and maintenance phase of the Magnox decommissioning.

Skips were used to move and store fuel and take up a lot of volume in the spent fuel pools, about 1 m^3 per skip. There are approximately 3000 skips at nuclear installations such as Magnox reactors and Sellafield in the United Kingdom. The estimated cost of storing one skip, for its lifetime, is £500,000 [143] (Fig. 8.26).

In Nov. 2014, a disassembly line was successfully tested that uses 3D laser scanning and robotic laser cutting to dismantle and size skips for recycling. The test occurred at Hinkley Point Magnox site. There are a total of 2500 skips stored at Hinkley Point A and Sellafield [144]. The disassembly process also included CNC robotic milling

Fig. 8.26 Automated Fuel skip sectioning using robotic laser cutting.

of high contamination areas to meet the recycling limits. The milling dust created was used to fill void space of waste packages to be disposed of at Drigg, the United Kingdom's low-level waste disposal land fill. Laser cutting is used to divide them into five pieces. Each piece is then passed into the five axis CNC milling machine, where it is scanned by a 3D laser and the milling machine can cut about 1.5 mm off each exposed surface. The cutting dross and the milling swarf form a mass of just over 50 kg, compared to the 450 kg weight of an empty skip. The remaining decontaminated material is melted and recycled. Despite the relatively high capital investment in a laser cutting system and a multi-axis milling machine, the potential cost saving for just 300 skips is estimated at £30 million [143]. The system processed all the radioactive skips and Hinkley Point and is being used to process skips shipped from Sellafield [144].

8.5.2 Underwater laser cutting

The capabilities of underwater laser cutting were recently tested by the NDE in the United Kingdom. Laser cutting underwater for processing skips has several advantages: in situ size reduction and consolidation, reducing radiation exposure by utilization of water shielding, containment of most radioactivity in water, not requiring special dismantling facility. The system uses air to artificially create a dry zone on the surface of the metal with three gas jets. TWI demonstrated the technology cutting C-Mn steel and found that the cutting performance of the fiber laser was similar underwater as in air. In preliminary demonstrations, a steel plate 12 mm thick, submerged under 300 mm of water, has been cut at a speed of approximately 0.4 m/min. [145] The only difference was that the dross created adheres to the part better when cutting underwater, which minimizes the amount of radioactive dross released [144] (Fig. 8.27).

The underwater cutting capabilities were tested and the airborne radioactivity was released in bubbles; then the radioactivity of the water was tested. Very fine cuts of a few millimeters were achieved, as seen in Fig. 8.25 (Fig. 8.28).

Fig. 8.27 Underwater laser cutting set-up.

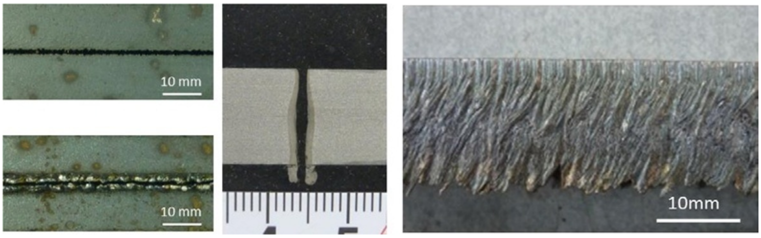

Fig. 8.28 Underwater laser cutting test cut dimensions.

Other laser underwater cutting technologies have been developed. An underwater cutting and welding technique is required for removal of irradiated materials like 4.2 mm thick zircaloy pressure tubes and up to 6 mm thick steel in reactor internals. This has been done by using a fiber-coupled 250 W average power pulsed Nd:YAG laser [146].

8.5.3 Arc saw

An arc saw is a form of metal disintegration machining (MDM) that uses a circular blade-like electrode to cut metal [147,148]. The electrode cuts metallic objects by melting a narrow kerf into the object. It is effective in cutting high conductivity materials such as stainless steels, high alloy steels, aluminum, copper, and Inconel [149]. In the 1970s the use of an arc saw for nuclear applications was investigated by the Fuel Cycle Program Office of the US Department of Energy when they initiated a program at the Pacific Northwest Laboratory to develop the arc saw as a tool capable of removing the end fittings from spent nuclear fuel bundles [150]. A special arc saw for this purpose was designed, installed at the Pacific Northwest Laboratory, and satisfactorily operated to remove end fittings from simulated, nonradioactive fuel bundles. Several simulated fuel bundles were cut to demonstrate that the arc saw met design specifications. Although the arc saw development program was curtailed before significant performance data could be collected, tests indicated that the arc saw is a good means of cropping spent fuel bundles and is well suited to remote operation and maintenance. The electric arc saw was initially considered in late 1976 for incorporation into the head end of a conceptual light water reactor (LWR) fuel reprocessing plant where the saw would remove the end fittings from spent nuclear fuel bundles. The original concept was to utilize the arc saw to cut off the end fittings to facilitate disassembly of the fuel bundle into fuel rods which would continue through the reprocessing cycle. It basically comprises a rotating, toothless metal blade, a direct current power supply, and controls that feed the blade into the workpiece (Fig. 8.29).

The cutting action is derived from the direct current arc between the blade and the metal workpiece. This arc melts the portion of the work in the saw kerf, which is expelled by the rotation of the blade. Several features of the arc saw that made it very attractive for remote operation in a radioactive work area are the following:

- no physical contact between the saw and the work (no pressure on the work)
- easily adapted to remote maintenance
- excellent positioning control for operation inside a hot cell

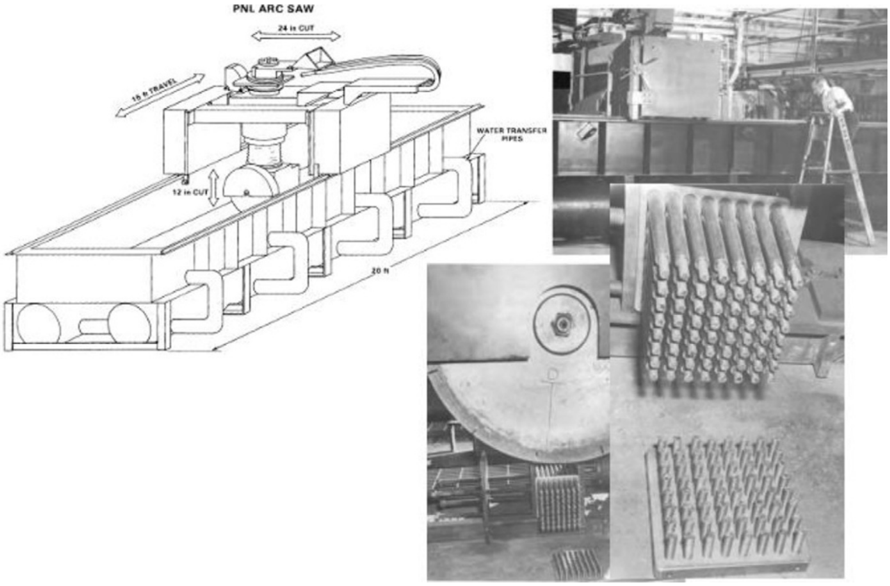

Fig. 8.29 Pacific Northwest Laboratory Arc Saw Tested for cutting spent fuel bundles.

- only the saw head and drive are inside the hot cell; power supplies and electronic controls are outside
- rapid cutting action; high throughput.

It has since been applied, under water and remotely operated, at the Japan power demonstration reactor (JPDR) for segmenting the body portion of the 250-mm thick carbon steel reactor pressure vessel (RPV) (Japan Atomic Energy Agency, n.d.). The highly activated portion of the RPV was cut into blocks using an arc saw cutter. Arc saw cutting was proven to be effective in preventing the release of contamination, in addition to minimizing the radiation exposure of workers [149,151,152] (Fig. 8.30).

8.5.4 Diamond wire cutting

Diamond wire cutting is not a new technology. It has been used at most decommissionings for cutting concrete and in specialized applications such as cutting the reactor vessel nozzles at Connecticut Yankee. Zion diamond wire cutting has been used more extensively than at previous decommissionings to replace applications such as plasma arc cutting of piping and components [153]. Diamond wire cutting use was expanded to segmenting steam generators at the Rancho Seco decommissioning. The Rancho Seco Steam Generators are of Babcock & Wilcox (B&W) design and commonly known as once-through steam generators (OTSGs). The B&W design consists of two such steam generators, each approximately 80 ft in height, 12 ft in diameter, and over 550 tons in weight. These steam generators were successfully cut in half using diamond wire cooled with carbon dioxide (Fig. 8.31).

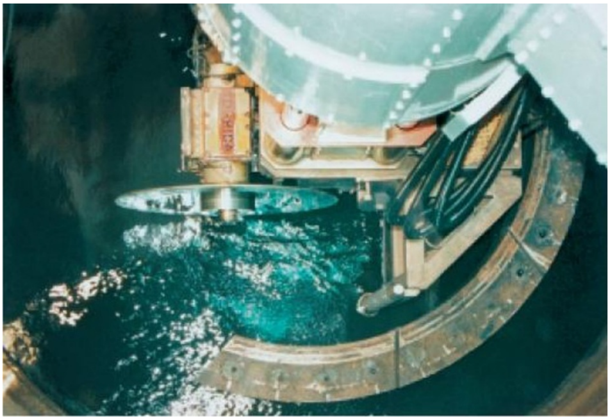

Fig. 8.30 Mast type arc saw cutting system employed in the vertical cutting of an RPV at the JPDR decommissioning project [182].

Fig. 8.31 Rancho Seco Steam Generator Diamond Wire Cut [154].

Diamond wire segmentation was later used to section and dispose of St. Lucie's U-tube steam generators that were stored horizontally at a facility in Memphis Tennessee. Zion used the technology to section three large U-tube steam generators in the originally installed vertical configuration. The technology and expertise in using it has evolved to allow successful application to significantly contaminated items such as steam generator U-tubes without excessive wire breaking, pinching, or airborne radioactivity generation.

Zion also expanded use of diamond wire cutting to replace conventional torch cutting methods for piping removals. Occupational safety requirements for plasma arc cutting of stainless steel to monitor and limit exposures to hexavalent chromium had significantly impacted the use this technique at the Zion decommissioning. The project used wire saws when sizing the reactor coolant system piping; once set up the cut is made remotely, reducing radiation exposure, swarf is captured, and airborne radioactivity was not generated even when cutting the steam generators and reactor coolant piping. The cut surface is smooth and minimized the prep time required to weld on end shields to reduce radiation levels for handling and shipping of large diameter reactor coolant piping.

8.5.5 Oxy propane cutting

Zion decommissioning successfully used oxy-propane torch cutting to segment the reactor vessel once the internals had been removed to allow shipment of the segmented vessel by gondola rail car for disposal [155]. Trojan, Maine Yankee, and Connecticut Yankee reactor vessels were removed, placed in shipping canisters, and shipped by barge for disposal. Closure of the Barnwell Waste Disposal site to most US generators and the inability for West Coast plants to ship vessel packages through the Panama Canal foreclosed this option for later decommissionings. The first successful completion of a large commercial reactor vessel segmentation in the country was Rancho Seco in 2008. That plant's reactor pressure vessel was segmented into 21 pieces and shipped offsite to a low-level radioactive waste facility. The Zion project used specially designed ventilation and filtration with a robotic fixture that included jacking stands and handling equipment to segment the vessel into 17 sections using an oxy-propane torch. The Zion Station project was the first to use the large-scale application of thermal cutting (oxy-propane) technology, which resulted in a much quicker cutting time—1 month versus 7 months at Rancho Seco, where abrasive water jet technology was used.

8.5.6 Robotics

As discussed in Section 8.3.2 BIMs are being widely used in various industries. Coupling these models with GPS or location aware Wi-Fi networks and remote, semi-autonomous or fully autonomous robotics systems has the potential to greatly lower costs, increase safety, and enhance performance at decommissioning facilities. Systems have been developed to work with all types of mobile equipment, including trucks, bucket loaders, bulldozers, excavators and Bobcats by various manufacturers. When integrated with IoT technologies such as RFID tags these systems provide monitoring, assignment, and tracking equipment, tools, and personnel to make industry work safer, more productive, and more efficient [66,156]. It is rapidly becoming feasible to accomplish a major portion of the D&D activities using heavy equipment remotely within the BIM, keeping personnel out of harm's way. This would reduce the safety and radiological coverage requirements and greatly simplify the planning and execution process.

These systems are a current capability [18,19], as is the existence of fully capable, remotely operated heavy construction equipment such as the excavators, trucks, bulldozers, etc. used to clear debris from Fukushima Daiichi site. Heavy equipment was operated remotely using X-Box controllers from command modules in sea/land containers up to 2 km away [157–161]. INTRA, Robotics INTervention on Accidents, maintained by EDF, CEA, AREVA, has remotely operated public works equipment (excavators, bulldozers) to clear up the pathways [162–166]. Fukushima uses roboticists and equipment outfitted with cameras to operate the equipment, relying on the video feed to the operator for monitoring and operating the machine safely. Systems such as Caterpillar's MineStar [59] tracks the position of the equipment within the 3D CAD model and allows operators to program the equipment to perform activities and drive routes within the BIM. This reduces human error and allows operators to synchronize and monitor multiple machines from a control room rather than guiding each machine individually from a controller.

The expansion of similar capabilities for the construction industry in general are being vigorously developed and investigated [20,21,189]. Use of this type of system coupled with location aware networks and BIMs could presently allow decommissioning to be largely performed from command centers. These systems are available for use now, but it may take the ascendancy of the gaming generation to management positions before they will be accepted for use at decommissioning facilities, even though they have proven themselves at Fukushima and are in everyday use in the mining industry (Figs. 8.32 and 8.33).

Location awareness capabilities for such systems such as Caterpillars MineStar [59] are predominantly GPS satellite-based and cannot be translated inside facilities at present, especially the heavy industrial structures associated with nuclear facilities. However, wireless Real Time Locating Systems (RTLS) are available that use time-of-flight information between wireless transmitters to triangulate the location of an active RFID or Wi-Fi tag to within a few meters [167–172].

More specialized robots are continuously being developed as well. These include the drones with 3D mapping and gamma camera capabilities discussed above, as well as use of 3D printing to fabricate cheap replaceable drones for under water applications such as ALEXIS in the UK (Fig. 8.34).

AVEXIS is a 3D-printed, mini-ROV being developed for use in UK decommissioning with the University of Manchester. 3D-printing construction allows design flexibility and modularity not found in traditionally manufactured ROVs. This allows cheap, efficient, on-demand production. AVEXIS is potentially the smallest inspection

Fig. 8.32 Remotely operated excavator used at Fukushima Daiichi from [157] and French INTRA ERELT T (Tele-operated Relay Robot) Mobile Wi-Fi Platform. [164]

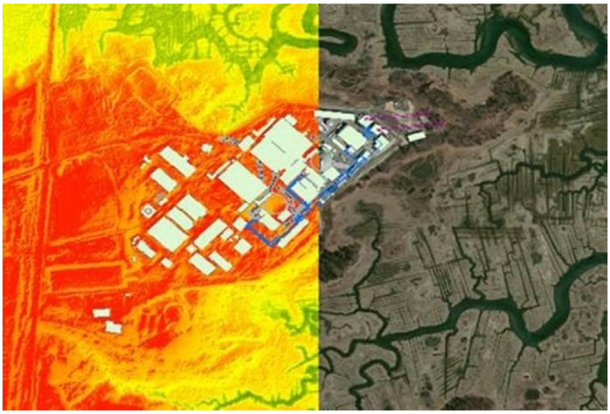

Fig. 8.33 3D GIS-CAD integrated map of a nuclear power plant showing a land surface LIDAR survey, satellite image and 3D buried piping. Courtesy of Radiation Safety and Control Services Inc.

Fig. 8.34 Alexis-D Printed mini-ROV [125].

ROV in the world at only 15 cm in diameter, allowing deployment through existing penetrations, between waste skips, and into pond bays for monitoring areas that were previously inaccessible in the UK spent fuel pools or ponds.

AVEXIS is a vehicle to deploy commercial-off-the-shelf (COTS) sensors, applicable to the targeted activity. For monitoring, AVEXIS has been tested with high-definition cameras, infrared cameras, and radiation monitors. This flexible sensor deployment, combined with the ease of 3D-printing, provides a cost effective solution for a range of pond deployments. Current work is developing the operability of AVEXIS before running active trials in the Pile Fuel Storage Pond in 2015/16 [125]. Other robots such as snake and spider robots are also being developed and used for decommissioning UK facilities [190,191]. Japan has developed a similar variety of robots and deployed them for the Fukushima reactor cleanups [192].

The French Atomic Energy Commission (CEA) has also developed a robotic arm specifically to perform decommissioning tasks [193]. MAESTRO was designed to perform multiple robotic functions using a variety of end effectors or tools. Cybernetix developed a control robot arm (the "maestro" arm) and a remote robot arm (or "slave" arm) that are manipulated from a control room by two operators (see Fig. 8.2), with the guidance of videos of the environment to be dismantled combined with 3D simulations. MAESTRO started its operations at the plutonium extraction plant, making laser cuts on dissolution tanks for reprocessing early in 2016. CEA is developing other specialized robots for dismantlement and decontamination tasks.

8.6 Conclusion

Technologies that can facilitate better planning and execution of decommissioning are rapidly evolving and available to be deployed to decommissioning projects. These include 3D CAD model and Wi-Fi connected data management systems and paperless work controls systems that can optimize work performance and project management. Off-the-shelf capabilities such as drone-to-CAD and 3D gamma cameras offer the potential to maintain an updated model of the site that can be used to track progress, organize data, and plan activities. Autonomous robotic capabilities are available to operate within the 3D CAD model with real-time tracking of assets through GPS and active and passive RFIDs. The increasing use of remotely operated and autonomous construction equipment in the mining and construction industries have the potential to afford greater efficiencies by removing personnel and all the requisite support and monitoring required from hazardous work environments. These technologies coupled with new cutting technologies such as laser cutting, arc saw cutting, and oxy-propane, oxy-petrol, etc. have the potential to reduce the time required to remove and size components and dismantle structures. In addition, development of specialized robots fabricated by 3D printing have the potential to lower the cost of and enable more widespread use of robots to obtain characterization data more efficiently and thoroughly than what is possible by manual methods. Statistical and probabilistic software for estimating and characterization can identify data gaps and high risk items to focus characterization and planning efforts efficiently. It is important to implement a continuous improvement process for decommissioning that includes adoption and integration of new technologies into project execution to make closure and decommissioning of existing facilities economically feasible.

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Decommissioning after a severe accident

9

C.A. Negin, M. Božik†, D. Stelmakh‡, H. Rindo§*
*CANegin&Associates, Washington Grove, MD, United States, †Nuclear and Decommissioning Company, plc., Bratislava, Slovakia, ‡Chornobyl NPP, Slavutich, Ukraine, §Institute of Applied Energy (IAE), Tokyo, Japan

9.1 Introduction

The conditions of nuclear facilities following a severe accident present difficult challenges caused by the combination of (a) uncontrolled release and spread of radioactive material and (b) damage to structures, systems, and components (SSC) as a result of exposure to high pressures and temperatures in areas normally protected by containment and system barriers. The breach of containment barriers can cause major impacts to and influence the course of decommissioning. Postaccident abnormal conditions are characterized by many uncertainties and unknowns (UUs) that are key factors that impact strategies, methods, and techniques for subsequent decommissioning.

In the long-term, there are three phases typically associated for dealing with the aftermath of a severe accident. These are (1) stabilization, (2) recovery, and (3) final decommissioning. Note that "final" decommissioning is used to indicate the time when the facilities can be dealt with by methods like standard decommissioning practices, whereas decommissioning alone refers to all the phases in general. Stabilization refers to the immediate aftermath of a nuclear accident; it controls conditions so that impacts to the environment and general public are minimized. Stabilization can involve repair and restoration of operating and structural functionality to achieve this minimum impact state. Recovery entails the planning and implementation of activities to limit, and subsequently reduce, the extent of abnormal conditions and prepare the plant to achieve a longer term, safer configuration. Recovery can be viewed as precursor to final decommissioning.

There is no clear-cut schedule milestone between any two of the three abovementioned phases; they can overlap. UUs are generated by the accident and its evolution, and they may initially be recognized, faced, and dealt with during both the stabilization and recovery phases. For example, treatment of liquid waste initiated during the recovery phase may continue well into the decommissioning phase. The schedule will evolve as access to SSCs is gained, either manually or with remotely operated equipment. Such access will be needed to identify the types and magnitude of actual and potential challenges. Access will allow detailed characterization (such as visual display of physical conditions and radiological contamination and intensity) that is essential for planning of work scope, schedule, and cost estimates. Such plans will evolve and change as understanding of conditions becomes better known.

Each severe accident is unique regarding the initiating cause and resulting conditions. Because of unpredictable conditions and evolution of a severe accident, it

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Table 9.1 Nuclear reactor fuel damage accidents

Plant (year)	INES scale	Country	Primary cause
NRX (1952) water-cooled, heavy water moderated	5	Canada	Design, operator error
Windscale (1957) gas-cooled graphite pile	5	UK	Lack of information for operators
SL-1 (1961) small prototype PWR	4	USA	Design
Chapelcross (1967) Magnox carbon dioxide-cooled, graphite moderated	4	UK	Design, operations
Fermi 1 (1968) sodium-cooled	4	USA	Design
Agesta (1968) water-cooled	4	Sweden	Design
St. Laurent (1968) gas-cooled, graphite moderated	4	France	Procedure
Lucens (1969) experimental gas-cooled, heavy water moderated	5	Switzerland	Channel flow blockage
Jaslovské Bohunice, A1, (1977) gas-cooled, and heavy water moderated	4	Slovakia	Operator error, blocked fuel channel
Three Mile Island (1979) PWR, light water-cooled	5	USA	Design, operator error, and relief valve stuck open
Chernobyl (1986) RBMK, water-cooled, and graphite moderated	7	Ukraine	Design, violation of operating procedures
PAKS (2003), PWR (Within a cleaning vessel outside of the reactor)	3	Hungary	Design, operational delay
Fukushima Daiichi (2011), BWRs, and light water-cooled	7	Japan	Tsunami, design

is difficult to define specific UUs that will be encountered during stabilization and recovery of a facility after a severe accident. The best that can be done to analyze UUs is to define categories and provide specific examples based on the experience of severe accidents such as A1 Bohunice, Three Mile Island Unit 2 (TMI-2), Chernobyl, and Fukushima Daiichi, which are described in this chapter.

Table 9.1 shows all significant nuclear reactor fuel damage events in chronological order from 1952 to 2011 [1]. In this table, the INES scale [2] indicates the severity of the accident.

9.2 Developments on nuclear facilities' shutdown, recovery, and decommissioning after an accident

This section describes some of the activities at facilities that have undergone serious accidents. The report, "Experiences and Lessons Learned Worldwide in Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents" [3], is a comprehensive description of the total range of on-site activities following severe accidents. This reference includes subjects of stakeholder communication and involvement, planning, stabilization, characterization, damaged fuel management, final decommissioning and site remediation, and accident waste management. This reference combined the experience from the cases described in this chapter and others.

Descriptions of accidents and immediate stabilization phases described in this chapter are included to establish the background. The bulk of this section is given to planning and implementation of recovery and planning for final decommissioning. Activities in this section range from those closer in time to the accident (mostly, recovery) to those leading to the final decommissioning. In each case, these activities depend on the specific circumstances of the accident and the time elapsed since its occurrence.

9.2.1 Fukushima Daiichi

9.2.1.1 The accident

At 2:46 p.m. on Mar. 11, 2011, the Tohoku-Chihou-Taiheiyo-Oki Earthquake affected an area that ranged from off-shore of Iwate Prefecture to the Ibaraki Prefecture. All the operating reactors were automatically shut down. Distance from the Fukushima Daiichi Nuclear Power Station (NPS) to the epicenter was 178 km.

At the Fukushima Daiichi NPS, the subsequent arrival of the tsunami, which was one of the largest in history, caused flooding of many cooling seawater pumps, emergency diesel generators, and power panels. There were station blackouts for Units 1–5, and all the cooling functions using AC power were lost in these units. Consequently, the fuel in each unit was exposed without water immersion or flooding, causing damage to the nuclear fuel cladding. Radioactive materials in the fuel rods were released into the reactor pressure vessels. The chemical reaction between the fuel cladding (zirconium) and steam caused the generation of a substantial amount of hydrogen.

Later, in Units 1 and 3, explosions of the hydrogen leaking from the primary containment vessels destroyed the upper structures of their reactor buildings. Another explosion occurred at the upper structure of the reactor building in Unit 4 where all the fuel had been removed from the reactor well before the earthquake and stored under water in the spent fuel pool. The Unit 4 fuel was not affected by the loss of cooling.

In Fukushima Daiichi Units 5 and 6, one of the emergency diesel generators for Unit 6 was in operation. By connecting a power cable to Unit 5, cooling water was supplied to the cores of both units. After the restoring the residual (decay) heat removal function a, Units 5 and 6 achieved cold shutdown.

9.2.1.2 Examples of stabilization objectives continuing into the recovery phase

Some of the stabilization phase for Fukushima Daiichi activities and their near-term objectives are shown in Table 9.2. These immediate challenges were faced by the plant operators for which the objectives were successfully achieved to allow moving on to the recovery phase.

Table 9.2 Some Fukushima Daiichi stabilization objectives

Stabilization activities	Objective
Cooling of the fuel and fuel debris	Cold shutdown with temperature below 100°C within the reactor system and below 65°C in the spent fuel pools with the ability to maintain those conditions
Monitoring of plant conditions	The ability to detect increases in temperature, pressure, and radiation are established with instruments
Criticality prevention	Increases in reactor or fuel pool temperatures are detected and means are in place for actions should the increase be attributed to neutron criticality
Ventilation and hydrogen control	Significant increases in concentration or accumulation of hydrogen within building spaces and reactor systems are prevented Airborne concentrations of radioactivity are controlled in spaces where humans are working
Reactor building structural stability	The reactor buildings' structures have been repaired and reinforced to provide safe enclosure for future work to remove the fuel in the pools
Containment of scattered radioactive materials	Radioactive materials on the site outside of buildings are prevented from windblown distribution off-site. Site boundary monitoring is in place to indicate if there are increases being transported off-site
Contaminated water	Contaminated water has been collected and processed to reduce radioactivity and/or is being stored
Radioactive wastes	Radioactive waste external to buildings has been collected and is stored or covered

Of those listed in the table, the continuation of the activities for contaminated water and managing radioactive wastes are further described. It is important to understand that these two activities are only two of many not addressed in this report.

9.2.1.3 Processing the contaminated water

Prior to 2016, about 400 m^3 of groundwater flowed into the accident facilities every day, and it became contaminated when contacting the fuel debris and contaminated surfaces, then passing into the turbine building. In addition, water for the cooling of the nuclear reactor (fuel debris) requires a 400 m^3/day. Therefore, the contaminated water flowing out from turbine building was about 800 m^3/day. This quantity of contaminated water then requires cleanup processing.

Cesium-137 is a primary radionuclide of concern in the contaminated water. Cesium is removed by two systems: the KURION (backup system) and SARRY (used for normal operation). After that, the contaminated water is introduced into the desalinization equipment (Reverse Osmosis membrane) to remove the salt for reuse of 400 m^3/day. About 400 m^3/day of surplus water is stored in medium- to low-level tanks on the site.

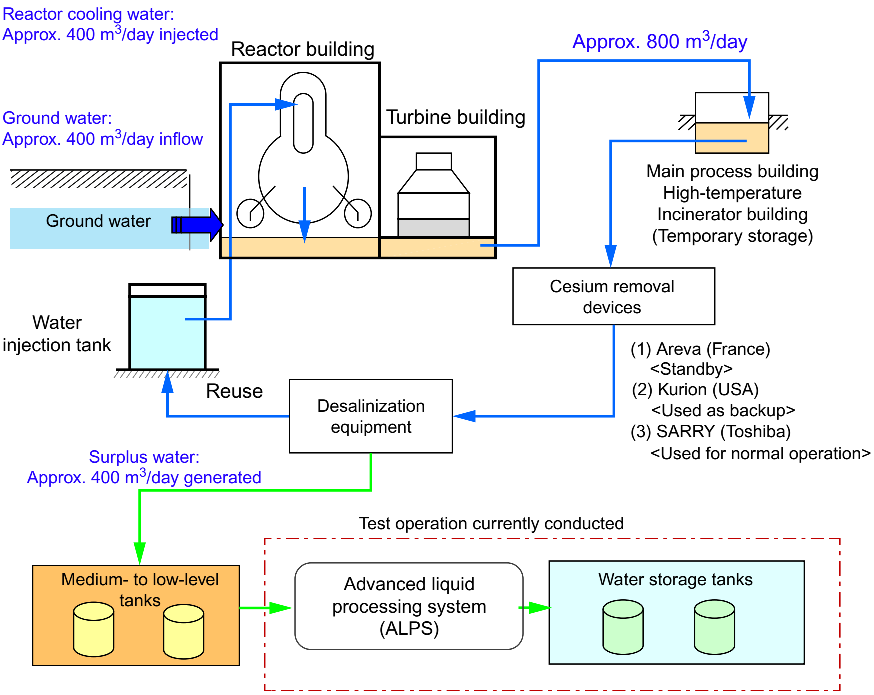

Fig. 9.1 The Fukushima Daiichi contaminated water treatment system.

The Advanced Liquid Processing System (ALPS) was then put into operation and can remove most nuclides to concentrations that are sufficiently low, except for tritium. Three sets of ALPS are installed at the site; however, a more advanced system will be installed to reinforce the processing capacity. The contaminated water treatment system is shown in Fig. 9.1.

Cesium-137 in the contaminated water of the reactor vessel reaches equilibrium in approximately 1.5 years after an accident. Future management of cesium will be primarily to continue removal of relatively small amounts that will be released while retrieving fuel debris.

9.2.1.4 Management of tritium

Tritium is a naturally existing radionuclide, and the background levels in the environment are about 0.01 Bq/g. Because the inflow of groundwater is extremely low, the content of tritium is in equilibrium with the leaching from the fuel debris. The half-life is 12.3 years and the biological half-life is 12 days.

Tritium cannot be removed with the installed contaminated water processes. When the leak points of the reactor pressure vessel are repaired and an inflow of groundwater and an outflow of contaminated water are prevented, a closed loop will be established for cooling the fuel debris. If all tritium was accumulated in this loop, the radioactivity concentration of tritium is estimated to be less than 1×10^5 Bq/mL. The remaining tritiated water will be stored in the tanks with the processed water [4].

There are several methods to remove molecular tritium from water, but any of these methods are not realistically feasible in view of the very low concentrations and with current removal technologies. If such separation were to be possible, it is thought that a risk of the pollution by leaks would be big as for storing a large quantity of processed water containing highly concentrated tritium for a long-term.

Tritium is a naturally existing nuclide. If the concentrations at Fukushima become close to background levels, it will be low enough such that the environmental risk of releasing it may be acceptable. However, before that can be considered, it is important for the stakeholders to understand this process.

9.2.1.5 Preventing inflow of groundwater

Preventing the inflow of the groundwater into the site is a major challenge. Three methods as described below are being put in place to prevent groundwater intrusion.

Bypassing ground water flowing to the sea side from the mountainside is achieved by pumping and diverting around buildings. Changing the passage of the water reduces the water level around the building. To prevent contaminated water within the buildings from flowing out, reducing the flow volume of the water into the building is increased step-by-step. This method reduces the groundwater inflow from about 400 m^3/day to about 100 m^3/day.

Subdrains existed prior to the accident to prevent of inflow of groundwater into the basement of the buildings and to prevent a buoyancy effect to act on the buildings. This system performance before the accident pumped up about 850 m^3/day of groundwater. The subdrains were rendered unusable by the tsunami; however, a restoration plan is under consideration to control the inflow of the groundwater into the building. Radioactive material released in the atmosphere can result in contaminated rainwater water that may flow in the subdrain pit. Therefore, a judgment for processing the subdrain water to bypass the site depends on inspection of the system and characterization of the collected water.

Installation of a landside impermeable wall surrounding Units 1–4 can block groundwater inflow. A frozen soil method has been selected and is in the process of testing.

9.2.1.6 Characterizing the radioactive solid waste

The solid waste of Fukushima Daiichi NPS is different from solid waste from conventional nuclear power plants. Common characteristics of the Fukushima Daiichi solid radioactive waste are the following:

- Failed fuel elements were scattered in the reactor vessel and/or relocated out of the reactor pressure vessel into the primary containment vessel.
- Most forms of contamination are surface contamination except for activated materials and are captured internally by melting during the accident.
- Data for the locations and quantities of the radionuclides, particularly data of long-life nuclides, are limited.

The waste contains relatively large amounts of fission product radionuclides from the nuclear fuel, activation radionuclides from the reactor core components, salt from the emergency use of seawater, and other hazardous materials resulting from the tsunami flooding. Radioactive solid waste including such materials has various technical issues to be solved for packaging and disposal.

Characterization of the radioactive solid waste is very important for future dismantling of the plant. It is expected that the nuclide composition of each waste and features of contamination level can be estimated to some extent by the end of Mar. 2017. Techniques to analyze nuclides difficult to measure and inventory evaluation techniques will be developed. Even at this point, however, data on the characteristics of the waste is still limited; therefore, characterization will be continued. Based on this information, the applicability of processing and disposal techniques will be evaluated. In addition, the operation of new nuclide analysis facilities will begin in 2018 to accelerate waste analysis. Because the schedule has been delayed. It will start the operation in this year.

Based on the information gathered by the end of Mar. 2017, a report on the "basic concept on processing/disposal of wastes" will be compiled in Mar. 2018 and be used to begin a regulatory study. Continuing beyond Mar. 2018, a future radioactive material analysis and research facility will be used to characterize wastes, accumulate analysis data using development technologies, and improve the accuracy of inventory evaluation. As a result, a processing facility will be installed in the site around after Apr. 2021, when production-level packaging of waste is expected to begin.

9.2.1.7 Managing the radioactive solid waste

The amount of the radioactive solid waste generated directly during the accident is shown in Table 9.3. This is the amount currently being kept and managed on-site.

Estimating the precise volumes for future waste management planning is very difficult because in addition to current knowledge, the amounts of various waste types will depend on the decommissioning methods and efficiencies during fuel debris removal

Table 9.3 Summary of the waste storage and their capacities (as of the end of 2015)

Category	**Storage method**	**Quantity (m^3)**	**Storage capacity**
Debris less than 0.1 mSv/h	Outdoor accumulation	115,600	177,900
Debris 0.1–1 mSv/h	Sheet covering	31,400	57,300
Debris 1–30 mSv/h	Temporary storage facility/tent and containers	25,900	27,700
Debris over 30 mSv/h	Containers	6,200	12,000
Debris total		*179,100*	
Tree trunks and roots	Outdoor accumulation	66,700	81,500
Tree branches and leaves	Temporary storage for trimmed trees	18,400	24,900
Trimmed trees total		*85,100*	

and, ultimately, the demolition of facilities and site cleanup. This will only be known as the scenario evolves and the many current uncertainties are resolved.

In addition, during future operations of ALPS, a large amount of secondary radioactive solid waste will be generated [5]. Large amounts of iron oxide sludge and carbonate sludge are especially generated as a secondary radioactive solid waste; however, it is currently difficult to take samples to analyze the radionuclides for structural problems. These radioactive wastes should be analyzed to know the contained nuclides for future processing/treatment. It is necessary to reduce the volume of radioactive solid waste by incineration of burnable waste etc. because about 3/4 of the storage area has already been occupied by radioactive solid waste. For processing/treatment and disposal of the radioactive solid waste, radionuclide analysis should be accelerated. The new analysis facilities are going to be installed in Fukushima, but the analysis method is developed by JAEA. Analysis time is shortened by 1/3, compared with a conventional analysis system [6]. Based on these results, the mid- and long-term roadmap indicates that it is possible to set up a general plan of processing/treatment and disposal of radioactive solid waste by the end of Mar. 2018. The roadmap also indicates that it is possible to get the technical prospect for safety measures for treatment and disposal of the radioactive solid waste by 2021.

Various options not only in terms of technical perspectives but also in terms of social perspectives are possible for treatment and disposal of radioactive waste. As for the end date of the decommissioning, international expert cooperation is necessary, and relevant information should be shared among stakeholders. In radioactive waste disposal, the assessment of disposal system barrier performance is necessary with radiotoxicity and chemical form; and the physical and chemical properties of solidification need to be considered. As well as conventional disposal forms, new disposal forms should also be considered.

9.2.1.8 Fukushima's path forward

Current activities toward decommissioning are steadily progressing. Radioactive waste processing/treatment and disposal and decommissioning of Fukushima Daiichi NPS are long-term and wide ranging works and should be performed while keeping in mind stakeholder involvement. Optimizing the entire process through appropriate management and flexibility per the situation are very important in future activities.

Before dismantling the facilities, the fuel debris should be removed from the reactor systems. The removal method of the fuel debris will be decided upon investigation of the status of the pedestal, fuel debris, and the result of various R&Ds.

9.2.2 Chernobyl NPP decommissioning and Shelter Object transformation into an environmentally safe system

The Chernobyl Nuclear Power Plant (Fig. 9.2) was commissioned in 1977 with four water-cooled, graphite moderated RBMK-1000 reactors. Unit 4 was destroyed in the 1986 accident. The reactor core of Unit 4, safety systems, and physical barriers were destroyed (Fig. 9.2, left). After 6 months, the large steel and concrete structure Shelter

Fig. 9.2 View of the Chernobyl nuclear power plant today.

Object (SO) covering the nuclear reactor No. 4 building was constructed (Fig. 9.2, right). The current status and consequences of the Chernobyl accident can be reviewed in Refs. [7] and [8].

Following the accident, Units 1, 2, and 3 operated until they were shut down between 1991 and 2000. Shutdown was in accordance with the arrangements between G7 governments, the Commission of the European Communities, and the Government of Ukraine.

The Chernobyl NPP is located within an exclusion zone area contaminated with long-lived radioactive contaminants from the 1986 accident. Considering there are no prospects for constructing new energy and other national economy facilities on-site, it has been judged to be unreasonable to perform decommissioning to a greenfield end state. The plan for long-term storage is described later in this chapter.

9.2.2.1 Stabilization and recovery activities

In the years since the accident, several important stabilization activities have been completed or are in progress. Some of these are as follows:

- All the spent nuclear fuel, including damaged fuel, has been removed from Units 1, 2, and 3. It is stored underwater in a pool within a storage facility.
- Preparations were completed and the authorization to perform the final shutdown and preservation stage was obtained in 2015. The main objective of this stage is to establish the condition at Units 1, 2, and 3 for their long-term safe enclosure under surveillance with minimum resource consumption.
- Activities on dismantling of structures external to the nuclear reactor systems and components not affecting the safety and not needed for work at a later stage of decommissioning are in progress. Equipment totaling 9200 tons were dismantled, for which 90% of the metal was decontaminated and released from regulatory control. The remainder was disposed as radioactive waste. Activities associated with the dismantling of Turbine Hall-2 equipment that began in 2016 are expected to dismantle another 20,000 tons of metal through 2020.
- The ChNPP cooling pond decommissioning is underway. The ChNPP cooling pond is an artificially created water body with an area of 22.9 km^2. The operational water level was 7 m higher than the water level in the Prypiat River. It was contaminated with radioactive contaminants from the accident. The cooling pond is decommissioned by terminating water input and allowing the water level to lower naturally. Radiation and environmental monitoring of the cooling pond decommissioning are being performed.

9.2.2.2 Recovery infrastructure

A significant part of the infrastructure for the ChNPP decommissioning is conducted within the framework of material and technical assistance to Ukraine from the international community. These include the following:

- Industrial Complex for Solid Radioactive Waste Management (ICSRM)—activities to prepare for commissioning are in progress (scheduled commissioning:2017).
- Liquid Radioactive Waste Treatment Plant (LRTP)—construction was completed. In 2014, a separate permission for LRTP operation was obtained.
- A Complex for Manufacturing Steel Drums and Reinforced Concrete Containers for radioactive waste storage and disposal (CMD and C RAW); the facility began operation in 2012.
- The Interim Dry Storage Facility for Spent Nuclear Fuel (ISF-2) has a scheduled commissioning for 2017. This will eliminate the need for the current wet storage.
- Facility for Release of Materials from Regulatory Control—a contract for its construction is planned for 2017.

9.2.2.3 Project for transforming the SO to an environmentally safe system

Currently, works on turning the SO into an environmentally safe system are an essential part of activities being implemented at the ChNPP site. A State Specialized Enterprise, "Chernobyl NPP" was established for comprehensive solution of problems with the Chernobyl NPP Unit's decommissioning and the SO transformation. The strategy for the transformation of the SO into an ecologically safe system is achieved through the implementation of three main stages of progression shown in Fig. 9.3. Stage 1, the project for the stabilization of shelter building structures, was completed in 2008. This ensures sufficient safety through 2023.

Stage 2 is underway. It involves creating additional protective barriers and preparation for retrieval of fuel containing materials (FCM) and high-level waste (HLW). The New Safe Confinement (NSC) (Fig. 9.4) is a protective structure with a complex of technological equipment for the removal of FCM from the destroyed Unit 4 of the Chernobyl NPP, radioactive waste management, and other systems. These will transform this unit into an environmentally safe system and ensure the safety of personnel, the population, and the environment. The main building consists of the arch structure with a 257-m span from north to south, a height of 108 m, and a length of 150 m. The NSC structure is being

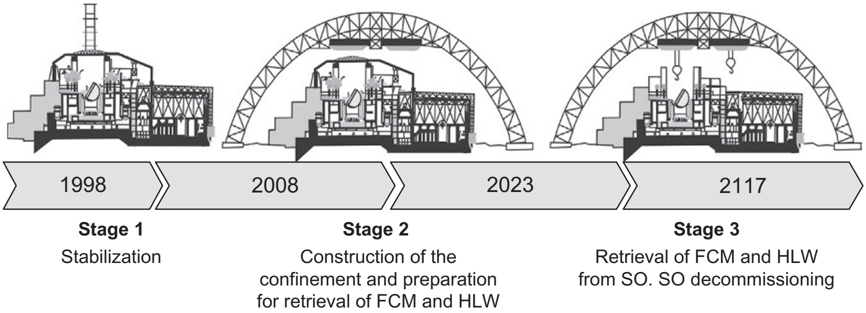

Fig. 9.3 Transformation of the Shelter Object into ecologically safe system.

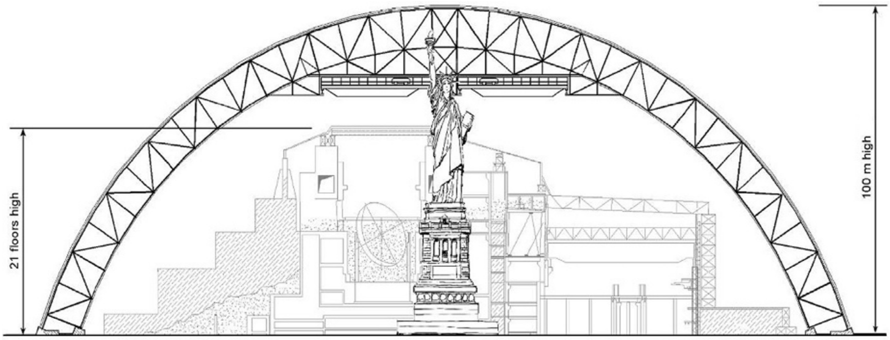

Fig. 9.4 Perspective of the new safe confinement.

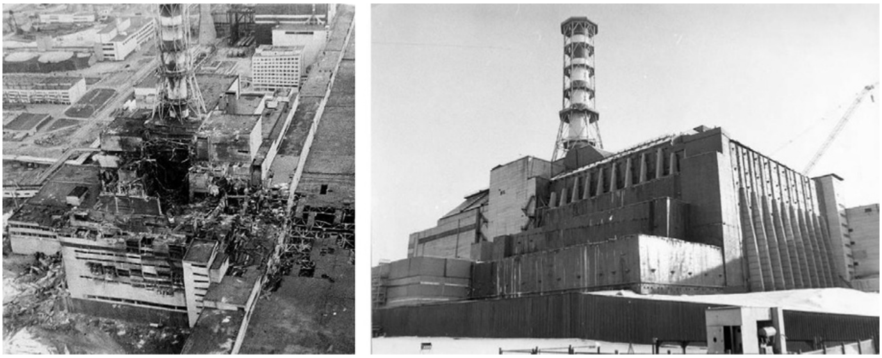

Fig. 9.5 A view of the postaccident Unit before and after construction of the Shelter Object.

constructed near the SO. Upon completion, the NSC structure was moved in November 2016 to its final location above the SO where outfitting of the internals equipment will be conducted and commissioned.

The completion of the second stage is scheduled for 2023 after dismantlement of the SO's unstable structures (Fig. 9.5). This will provide conditions for further activities related to SO transformation. The greatest hazard from the SO for the environment and the people is represented by the FCMs generated during the accident. Today, it is considered that the removal of the FCM stored inside the SO and its transfer into a controlled state are the main conditions for ensuring the SO's safe status. This task must be solved at the third stage of the strategy within the NSC's lifetime (100 years). A tentative overall schedule (Fig. 9.6) shows the key objectives for transforming the SO into an Environmentally Safe System.

9.2.2.4 Construction of the NSC

Preparation for NSC construction included cleaning-up and leveling of the area, preparation of trenches for constructing the foundations of the NSC erection, transport and service areas, as well as an erection area for preassembling the arch structures.

To ensure clearance for the arch sliding into position, it was necessary to construct a new ventilation stack of ChNPP Generation 2 and to dismantle the existing ventilation stack. The new stack was completed in 2012, including works associated with

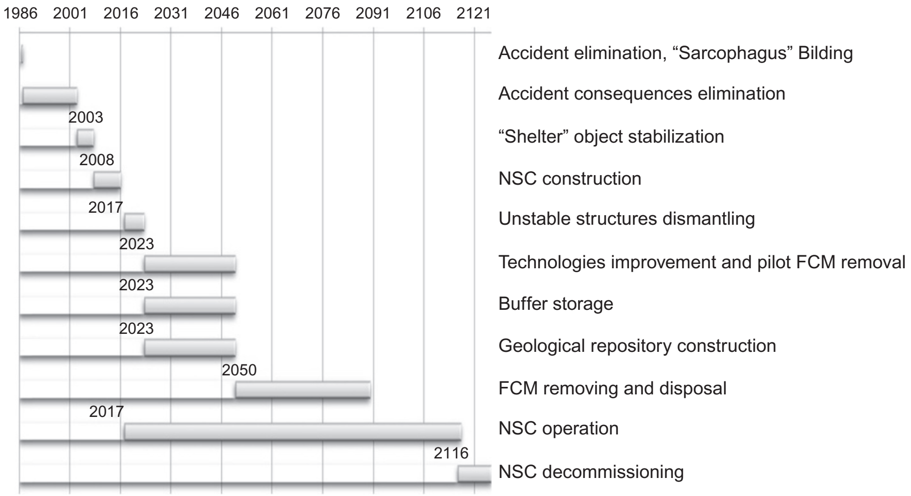

Fig. 9.6 Tentative schedule for implementing the SO transformation strategy.

Fig. 9.7 Beginning and near completion of one half of the main arch structure.

installation of external equipment (fire protection, radiation monitoring systems, etc.). Removal of the existing stack was carried out under severe radiation conditions; it was completed in Nov. 2013.

Assembling of the main arch structure began in Apr. 2012 (Fig. 9.7). The west and east halves of the Arch were fully connected on Jul. 24, 2015.

29 November, 2016 the NSC slid into place thus the successful enclosure of the heavily damaged Unit 4 at Chernobyl was completed. A system of hydraulics was employed to move the arch that weighs 36,000 metric tons and now the New Safe Confinement is the largest man made object ever built for movement on land (Fig. 9.8). Installation of technological equipment is being performed. The NSC commissioning is planned for Nov. 2017.

9.2.2.5 Importance of the NSC

The importance of the NSC is stressed by the event that occurred on Feb. 12, 2013. Partial failure of the wall slabs and light roof of the Unit 4 Turbine Hall occurred at the SO (Fig. 9.9). The area of damage was about 600 m^2. This structure was not a critical structure of the SO and there was no violation of limits and conditions of the SO's safe

Fig. 9.8 Installation of process equipment.

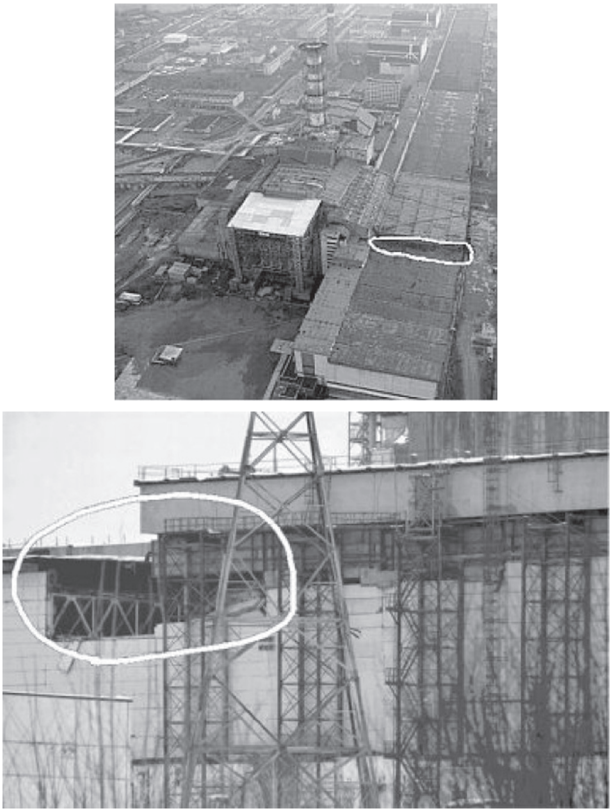

Fig. 9.9 Collapse of structures at the Shelter Object (area of collapse is shown in the *white circles*).

operation. No changes occurred in radiation at the ChNPP industrial site and within the exclusion zone. There were no injuries. However, this indicates the process of the SO structure's degradation.

In 2014, the integrity of the safe enclosure of ChNPP Unit 4 Turbine Hall was completely restored.

9.2.3 A1 NPP

The former Czechoslovakia was among the first countries in the world to develop and construct a nuclear power plant. This was powered by the heavy water reactor and known as the A1 nuclear power plant in Jaslovské Bohunice. Site preparation started in 1956 and the nuclear plant began construction 2 years later (see Fig. 9.10). The KS 150 reactor was designed in the Soviet Union and built entirely in Czechoslovakia. The heavy water moderated reactor used carbon dioxide for coolant; the plant's electrical output was rated at 150 MW. Postaccident management of A1 can be reviewed in Refs. [9] and [10].

The discussion of A1 in this section is based on the timeline shown in Fig. 9.11 that illustrates operations and shutdown through 1995, preparation for decommissioning through 1999, decommissioning activities to the present (2017), and plans through 2033. The following discusses the decisions related to the timeline and planning for the future.

Fig. 9.10 The A1 NPP during the construction.

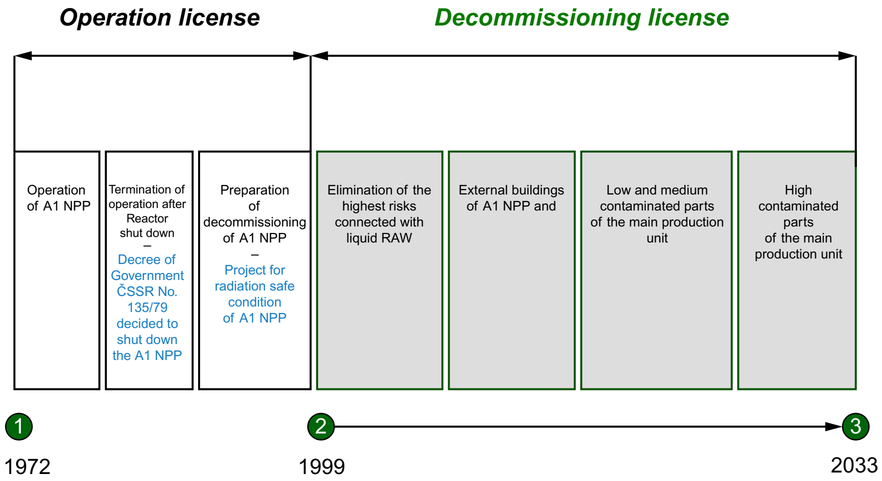

Fig. 9.11 Timeline for the operation and decommissioning of the A1 NPP.

9.2.3.1 Operation, termination, and preparation prior to decommissioning stages

A1 operated from 1972 to 1977 when it was shut down after two operational accidents that overheated and caused failure of some fuel elements. The final shutdown decision was taken in 1979 based on analyses of technical, economic, and safety factors. At that time, the experience of decommissioning nuclear power plants was very limited worldwide. Even more significant is that experience was almost nonexistent for dealing with conditions after an accident that had severely damaged nuclear fuel.

In Czechoslovakia at that time the necessary legislation providing framework for nuclear facilities decommissioning, or the technical conditions for execution of such activities, was absent. Therefore, aside from legislative and administrative conditions and staffing of activities, it was necessary to design and construct specific technologies for radioactive waste and spent fuel management, including the repository for final storage of the radioactive waste and the associated transport equipment.

The main problems prior to the decommissioning (1979–94) included the following:

- absence of legislation for decommissioning,
- absence of professional staff for decommissioning (need to train a large number of workers),
- lack of financial resources, during the operation of the NPP A1 funds for decommissioning were not set aside,
- lack of facilities for handling radioactive waste (handling, processing, transport, storage, etc.),
- lack of facilities for handling spent nuclear fuel and damaged spent nuclear fuel in special fuel capsules (handling, transport, storage, etc.),
- incomplete and inaccurate radiochemical, chemical, and physical characterization of RAW,
- specificity and diversity of RAW (sludge, ion exchange resins, ash, concrete, metal material, DW, Chrompik, chromo sulfuric acid, residues of heavy water, and air filters),
- contamination of equipment produces radiation fields, characterized by an increased dose rate in the area.

Activity carried out prior to decommissioning stages through 1999 included the following:

- Disposal of 572 spent fuel elements to Russian Federation beginning in 1993,
- Environmental measures and health safeguards,
- Research and development activities and infrastructure in support of decommissioning were financed by state budget,
- Analysis of the feasibility of decontamination of the primary circuit,
- Dismantling the secondary circuit and reactor auxiliary circuit, strengthening barriers to prevent leakage,
- Develop technical/economic/safety analysis of the A1 NPP; this analysis formed the basic provision for the government's decision on how to proceed with the A1,
- Establish technologies for radioactive waste (RAW) treatment and modification,
- Construction of the National Radwaste Repository in Mochovce and technical accessories by request of the Nuclear Regulatory Authority (NRA) of the Slovak Republic (SR),
- Establishment of the National Fund for Decommissioning,
- Elaboration of "The project for initiation of the A1 NPP to radiation safety phase"; the project was renamed to "A1 NPP Decommissioning—Stage I,"
- Acceptance of Project by NRA of SR: decision no. 137/99.

9.2.3.2 Decommissioning

While evaluating the A1 nuclear power plant decommissioning, three scenarios were considered:

- The first—power plant closure followed by surveillance and delaying the start of the decommissioning process by 30 years,
- The second—Safe enclosure of the reactor for 30 years,
- The third—Continuous decommissioning without delay.

The "Continuous decommissioning concept" was recommended and approved during the process of environmental impact assessment, and it was divided into five subsequent stages, based on the knowledge available at that time.

9.2.3.3 Stage I

The objective of the first stage was to establish safe radiation conditions without the presence of nuclear fuel and eliminate the possibility of uncontrolled release of radioactive material into the environment. The main scope was safe storage, transfer and processing of historical wastes. Technologies for management of materials from the spent nuclear fuel storage, such as cooling media and casings—which were not part of the transport to the Russian Federation—were constructed.

During this stage, decontamination and dismantling works on the original technological facilities also began. One of the specific technological systems, constructed during the first stage, is a vitrification line placed in the main production unit. The facility (Fig. 9.12) was designed and installed to stabilize the Chrompik medium that had been used to cool the spent nuclear fuel while it was being stored. During Stage I, vitirification converted the Chrompik into a glass matrix.

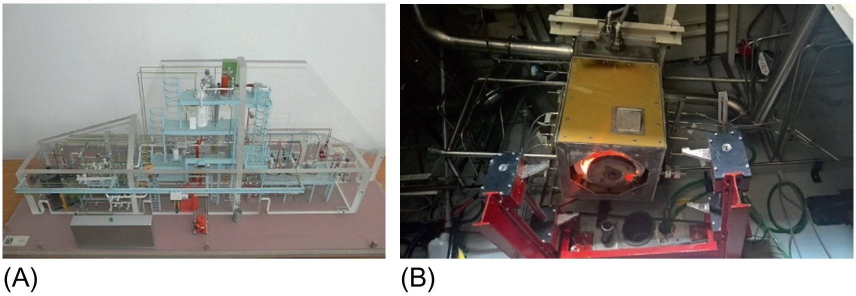
(A) (B)

Fig. 9.12 Model and equipment to vitrify Chrompik. (A) Vitrification unit model. (B) vitrification unit.

9.2.3.4 Stage II

Stage II is divided into four groups of tasks:

- Decommissioning of nonoperated equipment and facilities, reconstruction of the buildings.
- Management of radioactive waste.
- Management of contaminated soil.
- Technical support and protection of the environment.

The second stage was launched in 2009 with a primary objective of removing further environmental risk. The activities of this stage concentrate mostly on decommissioning of the external structures of the power plant, continuation of decommissioning of the long-term storage during stage II is described in detail in page 276, the issue of contaminated soils and concrete management, and on procedures of waste management from the main production unit.

During Stage II, the main activities focussed on the external buildings connected to the large-scale carbon dioxide gas tanks, on the heavy water system, and the primary circuit cooling system. In the waste water purification plant, the decommissioning concentrated on redundant and nonoperational technological parts of the station, storage space for the liquid waste, including removal of the external bulk tanks, and processing of sludge from these tanks. In addition, the groundwater and contaminated soils on-site are being remediated, sorted, and prepared for transport to be stored as very low-level wastes in the national repository.

Stage II also removed technological equipment and demolished seven buildings. Eleven of thirteen tanks were removed (Fig. 9.13).

Carbon dioxide coolant tanks were decontaminated while in place and excavated along with the surrounding soil. The tanks were reduced in size by cutting into rings. These were decontaminated to free-release levels and reduced in size for other use. 100% of inactive and 95% of active pipeline channels were removed.

Contaminated soil was removed, surveyed, and sorted by radioactivity levels (Fig. 9.14). Contaminated soil with an activity of from 300 to 10,000 Bq/kg is packed in large volume bags and moved to the central manipulation station for eventual transport to the very low-level activity waste repository in Mochovce. Soils meeting the strict legislative criteria for release into the environment are used for backfilling and ground contour of the JAVIS site.

Fig. 9.13 Decommissioning tanks.

Fig. 9.14 Surveying, sorting, and packaging contaminated soil.

In the main production unit, equipment associated with the heavy water circuit (Fig. 9.15), carbon dioxide cooling systems, and oil management were removed. Major large refueling machine components were scrapped (Fig. 9.16).

One of the most important activities is decommissioning the highly exposed long-term storage of spent nuclear fuel. The activities include successful transfer of the radioactive sludge (Fig. 9.17) from the long-term spent fuel storage pool into new tanks, from which the sludge is gradually retrieved and processed. The long-term storage pool also contains empty fuel containers from the spent nuclear fuel storage, which are gradually retrieved and cut into smaller fragments in special equipment designed for this purpose. Subsequently, the casings are decontaminated to an acceptable level, pressed, and placed into the fiber concrete containers and stored in the national repository in Mochovce. Containers with Chrompik residues, which were fixed inside, are sorted. The separated parts of the fuel containers are loaded and sealed in new casks that are temporarily placed in storage prior to the transport to the integral storage of radioactive waste.

Fig. 9.15 Remotely controlled teleoperator MT 80 fragmentation evaporator of D_2O.

Fig. 9.16 Current state of refueling machines on reactor hall A1 NPP.

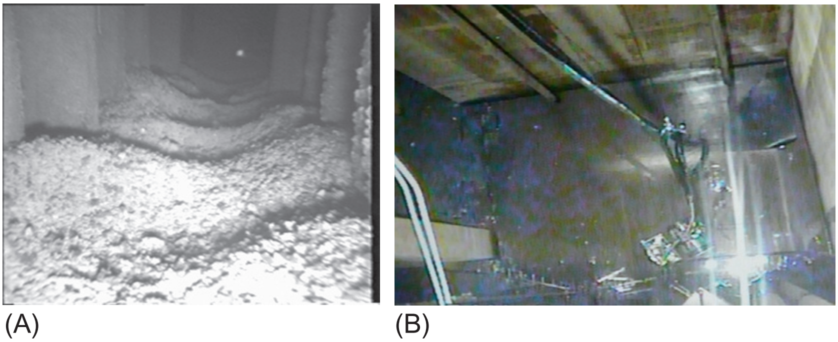

Fig. 9.17 (A) Sludge at the bottom of the LTSFS. (B) Bottom of the pool (LTSFS) during the sludge pumping.

9.2.4 TMI-2

The TMI-2 accident occurred in Mar. 1979. The TMI-2 accident was not as severe as Chernobyl or Fukushima because the reactor vessel and reactor containment integrity were maintained and there was no significant off-site contamination. The stabilization phase can be measured by the time required to begin removal of fuel debris; this was 6.5 years. The recovery, which was considered to end when all fuel debris was shipped, required another 4.5 years; however, another 3 years were needed to establish the current interim end state.

Transporting the fuel debris that could be removed without dismantling the facility was completed in Apr. 1990. The cleanup to meet the US Nuclear Regulatory Commission (NRC) postaccident safe storage criteria was completed and accepted by the NRC in 1993, with TMI-2 entering what is called “post-defueling monitored storage.” This is similar to what is otherwise referred to as “safe storage.”

The successful stabilization and recovery of TMI-2 established a valuable precedent of using government skills and resources at national laboratories for resolving technical challenges that the TMI-2 owner-operator did not have the means and authority to do alone. A second valuable precedent was the establishment of an on-site NRC office that, except for release of processed water and reactor building venting, was allowed to operate in a semiautonomous mode to conduct safety reviews and to approve new operations proposed by the TMI-2 owner-operator. At the completion of fuel debris removal, a comprehensive compilation of the technical and managerial challenges of the TMI-2 cleanup was written [11]. A key value of this reporting is that both negative and positive experiences were reported, which has proved to be a valuable reference for managers at subsequent accident sites.

The interim end state of the TMI-2 facilities was determined using a specification process similar to that described in Chapter 6 of the Nuclear Decommissioning Handbook [12]. The criteria for the conditions to be established were specified by the NRC. The water in the reactor systems was drained and processed to remove radionuclides except for tritium. This processed water was evaporated into the open air because downstream residents did not want it to be discharged into the river.

Establishing the interim end state involved estimating the amount of fuel debris currently remaining throughout the plant. The characterization of these materials was vital to exclude the occurrence of nuclear criticality. The amounts were determined to be approximately 1125 kg, of which 98.5% is within the reactor coolant system, the reactor pressure vessel, and the reactor building [13]. Access to remove these materials could not be reasonably gained during the postaccident cleanup because it would have required cutting large components and pipes in high radiation areas.

The only activities currently conducted at TMI-2 are a few maintenance routines and preventive maintenance for some systems. Routine maintenance includes checking and changing high efficiency particulate filters for the air being exhausted from the reactor building. This flow is passive to ensure no differential pressure conditions develop within the environment. A preventive maintenance procedure verifies that radiation conditions have not changed; the procedure includes a once-yearly containment manual inspection and survey. The control room is operational as needed for monitoring conditions and the few systems in operation, which includes electrical systems and control room ventilation. Preventive maintenance is performed on the motor control centers and ventilation fans and motors. A fire detection system is in place; however, there is no active fire suppression system. This is justified by the elimination of combustibles and minimizing ignition sources. If a fire is detected, the fire brigade from the adjacent Unit 1 would respond. The domestic water system is partially operational and is maintained to correct occasional leaks.

9.3 Selected IAEA activities in support of decommissioning after an accident

The IAEA responded in full to the accidents at Chernobyl and Fukushima Daiichi nuclear power plant (and to a lesser extent, other facilities damaged by nuclear accidents), through a range of collaborative activities and action plans. For example, the IAEA Secretariat acted to organize International Experts Meetings to analyze all relevant technical aspects and learn the lessons from the accident, in particular about postaccident decommissioning. The International Experts Meetings [14] and other international cooperation mechanisms brought together leading experts from areas such as research, industry, regulatory control, and safety assessment. These activities have made it possible for experts to share the lessons learned from the accident and identify best decommissioning practices, and to ensure that both are widely disseminated. IAEA reports draw on information provided by fact-finding missions and expert meetings as well as on insights from other relevant IAEA activities (e.g., international conferences). It is expected that additional information and analysis related to the accidents addressed in this chapter, and follow-up decommissioning will be continually generated and circulated within IAEA fora in the future.

Experience with severe accident stabilization, recovery, safe storage, and activities leading to final decommissioning is the subject of several technical publications by the International Atomic Energy Agency (IAEA). This began in 1989 at which time it was important to understand what lessons from the TMI-2 project might be of use for dealing with the accident at Chernobyl. A second purpose was to make the TMI-2 experience available for general understanding of the challenges in managing the postaccident situation. Refs. [15] through [16] represent the IAEA publications at that time that were developed to achieve these purposes.

Since Fukushima the IAEA has since published two comprehensive reports related to postaccident actions. The first Ref. [3] described postaccident lessons learned for four severe accidents. It addresses stakeholder communication and involvement, postaccident planning, stabilization, characterization, damaged fuel management, decommissioning and site remediation, and waste management. The second Ref. [17] compares experience with techniques, practices, and implementation using examples from five severe accidents. It also shows the applications of some standard decommissioning methods in postaccident situations.

The IAEA has also published *Nuclear Accident Knowledge Taxonomy* (NAKT) [18], which presents the basis for a systematically structured categorization of knowledge management for nuclear accidents. NAKT is a tool to search for information that includes, among other subjects, lessons learned and practical experience in addressing the consequences of such accidents. At this stage, this report describes the concept for and current progress on establishing a NAKT. It also describes the requirements for a software system called Nuclear Accident Knowledge Organization System (NAKOS) for search and retrieval of subject-specific information. One example of the application of a NAKT structure has been created by the Japan Atomic Energy Agency for information related to the Fukushima accident. It is located at http://tenkai.jaea.go.jp/english/sanko/index.html.

During the interim between TMI-2 and Fukushima there have been IAEA technical cooperation projects (TCPs) at A1 Bohunice, Chernobyl, and Fukushima. Activities for A1 and Fukushima are described in the following subsections.

9.3.1 Technical Cooperation Projects for A1 NPP

There have been five TCPs in support of the A1 decommissioning with the following titles and performance periods:

- Remotely Operated and Robotic Technologies for Decontamination and Dismantling of the A1 Nuclear Power Plant (2001–06).
- Managing (Historical) Radioactive Waste from the A1 Nuclear Power Plant Decommissioning (2007–08, 2009–11).
- Improving the Characterization Techniques for the A1 Decommissioning Project (2012–13).
- Supporting Decommissioning and Waste Management for the Chernobyl, Ignalina, and A1 Nuclear Power Plants (2014–15).
- Strengthening Intermediate Level Radioactive Waste Management for the A1 NPP Decommissioning Project (2014–15).

The technical focus of these projects has been wide ranging. They include, but are not limited to, conditioning of various waste streams, operational measurements and characterization of radioactive waste with several technologies and test protocols, contaminated surface characterization, immobilization matrices, and improvements of equipment for assurance of radiation safety.

These projects have also provided management support. One was training and qualification of decommissioning staff. A second was assistance in the establishment and coordination of common processes to transition to decommissioning with special focus on project management and engineering change control. Also in the management area was the theoretical and practical basis for professionals in the field of nuclear decommissioning of large components with complex geometries.

9.3.2 Fukushima

9.3.2.1 The Fukushima report

Following the Fukushima accident, the IAEA provided support by organizing the international community to provide and apply its experience with postaccident recovery actions. A meeting of experts [14] presented the experience from several severe accidents and for less serious accidents and environmental remediation of off-site contamination.

Since the accident at the Fukushima Daiichi NPP, there have been many analyses of its causes and consequences, as well as detailed considerations of its implications for nuclear safety, by IAEA Member States and international organizations signatory to international agreements on nuclear safety. For example, a meeting of the Contracting Parties to the Convention on Nuclear Safety was held in Aug. 2012 to review and discuss the initial analyses of the accident and the effectiveness of the Convention.

In Aug. 2015, the IAEA published The Fukushima Daiichi Accident Report by the Director General, along with five technical volumes prepared by international experts, assessing the cause and consequences of the accident. The publication brings together lessons learned from the accident and provides a valuable resource to all countries that use, or plan to use, nuclear power. It considers the accident itself, emergency preparedness and response, radiological consequences, postaccident recovery, and the activities of the IAEA since the accident. Volume 5 describes on-site stabilization and recovery activities at Fukushima from 2011 to 2014 [19].

The report on the Fukushima Daiichi accident is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 member states (with and without nuclear power programs) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review of the report. Additional internal and external review mechanisms were also instituted.

The report and the technical volumes distill and assemble lessons learned from the accident and provide a knowledge base for the future. They consider the accident itself, emergency preparedness and response, radiological consequences of the accident, postaccident recovery, and the activities of the IAEA since the accident. Measures taken, both in Japan and internationally, are examined [20–25].

9.3.2.2 Decommissioning peer reviews

Following the accident at TEPCO's Fukushima Daiichi NPS on Mar. 11, 2011, the "Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi NPS Units 1–4" (hereafter referred to as the Roadmap) was adopted by the Government of Japan and the TEPCO Council on Mid-to-Long-Term Response for Decommissioning in Dec. 2011. The Roadmap was revised in Jul. 2012, Jun. 2013, and Jun. 2015 [26–28]. The Roadmap includes a description of the main steps and activities to be implemented for the decommissioning of the Fukushima Daiichi NPS through the combined effort of the Government of Japan and TEPCO.

The IAEA organized three missions of the International Peer Review of the Roadmap, which were implemented within the framework of the IAEA Nuclear Safety Action Plan, in Apr. 2013, in Nov.–Dec. 2013, and in Feb. 2015. Those missions aimed at enhancing international cooperation and sharing with the international community information and knowledge concerning the accident to be acquired in the future decommissioning process.

The first mission was conducted with the main purpose of undertaking an initial review of the Roadmap, including assessments of the decommissioning strategy, planning, and timing of decommissioning phases, and a review of several specific short-term issues and recent challenges, such as the management of radioactive waste, spent fuel and fuel debris, management of associated doses and radiation exposure of the employees, and assessment of the structural integrity of reactor buildings and other constructions. The Final Report of the first mission is available on the IAEA webpage [29].

After the first mission, the Government of Japan and TEPCO revising the Roadmap took into consideration the advice in the first mission report. The revised Roadmap entitled “Mid-and-Long- Term Roadmap towards the Decommissioning of TEPCO’s Fukushima Daiichi NPS Units 1–4, revised Jun. 27, 2013” is available on the website of the Ministry of Economy, Trade and Industry (METI) [27].

The objective of the second mission was to provide a more detailed and holistic review of the revised Roadmap and midterm challenges, including the review of specific topics agreed upon and defined in the first mission, such as removal of spent fuel from storage pools; removal of fuel debris from the reactors; management of contaminated water; monitoring of marine water; management of radioactive waste; measures to reduce ingress of groundwater; maintenance and enhancement of stability and reliability of SSCs; and research and development (R&D) relevant to predecommissioning and decommissioning activities. The Final Report of the second mission is available on the IAEA webpage [30].

The third Mission of the International Peer Review involving 15 international experts was implemented from Feb. 9–17, 2015. The objective of the third Mission was to provide an independent review of the activities associated with revisions to the planning and implementation of Fukushima Daiichi NPS decommissioning. The Mission was conducted based on IAEA Safety Standards and other relevant safety and technical advice, aimed at assisting the Government of Japan in the implementation of the Roadmap [31].

After the third mission, the Government of Japan and TEPCO revised the Roadmap on Jun. 12, 2015, taking into consideration the progress of the revised one and the third mission report of IAEA. This Roadmap includes Unit 5 and 6 of Fukushima Daiichi NPS, which had shut down permanently [27].

9.4 Decommissioning following the accident recovery phase

When the postaccident recovery phase is completed and long-term stability has been established, decisions are needed for what is to follow. As of the current time, no nuclear power plants that have experience accidents have been fully removed. Three examples are briefly described for accident plants that have been place in a safe storage mode, referred to as SAFSTOR. The three are Windscale, TMI-2, and Chernobyl.

9.4.1 Windscale

Windscale Piles 1 and 2 at the Sellafield site in the United Kingdom were essentially blocks of graphite with aluminum-clad rods of uranium, other elements, and/or isotopes running through the otherwise solid graphite. Air was blown from one side over the graphite and the rods to cool them, while hot air was pulled out of the other end and vented through large discharge stacks. In Oct. 1957 a graphite fire in the reactor burned for 3 days, releasing radioactive contamination.

Over the following years, several surveys combined with review of other sources of information have concluded that the magnitude of damage in Pile 1 is 20 tons of degraded fuel and isotopes. The plant is currently in safe enclosure (using the existing structure) based upon the following rationale:

- Delay will allow the decay of radioactive isotopes;
- Financial assurance is required to allow the project to commence uninterrupted;
- The Windscale reactor is passively safe; and
- New technologies are assumed to be available for more safe and efficient decommissioning.

The passively safe condition is based on a balanced risk review across the Sellafield site, and the reactor is approved to remain in its current condition for a significant period subject to routine review. Ongoing justification is needed for continuing the operation of the facility under the deferral period, referred to as "surveillance and maintenance." The use of this terminology signifies recognition that Pile 1 is an operational facility that will be adequately maintained in its present form within an asset care program to replace worn out or obsolete equipment where necessary.

9.4.2 TMI-2

Today at the Three Mile Island site, TMI-2 is in a safe storage mode. The undamaged TMI-1 is operating normally and is planned to begin decommissioning in 2034. TMI-2's final decommissioning is based on a concept that will achieve complete dismantling and site remediation together with Unit 1. Like the Windscale rationale, this period of more than 50 years after the accident provides for substantial decay of the dominant radiation radionuclides (Cs-137 and Co-60). It also allows time to assemble a decommissioning fund for the estimated US $869 million (2009 reference year) required to decommission TMI-2 [32]. Another advantage is that technological developments will make decontamination and demolition safer and more efficient. Remote technology being developed for Fukushima will set precedents for final decommissioning of TMI–2.

9.4.3 Chernobyl

A "deferred dismantling" strategy has been decided for the ChNPP with the timeline shown in Fig. 9.18. This includes preservation with long-term (up to

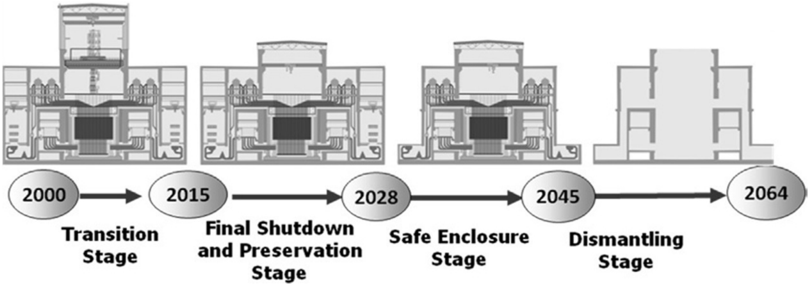

Fig. 9.18 SAFSTOR strategy for the ChNPP.

50 years) safe enclosure for most of the contaminated equipment that includes the primary circuit and reactor, which will be monitored and maintained. During this period, other contaminated and some non-contaminated equipment will be dismantled and removed. The end state objective is referred to as brownfield conditions, where actions on dismantling of equipment are performed and radioactivity of building structures is reduced to the levels of restricted release from regulatory control.

Dismantling of building structures and clearance of the ChNPP site area are not formally referred to as decommissioning. This activity is considered to be mitigation of accident consequences and remediation of the exclusion zone.

9.5 Concluding remarks

While the knowledge base for decommissioning and remediation activities under normal circumstances is well established, this is not the case when a facility is severely damaged by a nuclear accident. Indeed, the differences among accidents' causes and conditions following an accident show that every case is a challenge that will have unique aspects. In coping with the stabilization and recovery from an accident, it can be expected that situations will arise for which there is limited or no specific experience upon which to draw. There is room for improvement, relating to both technologies and organizational/management aspects. For example, the current advances of remote technology that will be needed for Fukushima did not exist at the time of A1, TMI-2, or Chernobyl. That said, it is observed that the amount of documented technical lessons from past accidents as well as nonaccident experience from decommissioning of sites other than for NPPs has been of value for the Fukushima challenge.

The accidents addressed in this chapter have contributed to improvements in operation and design of current and future NPPs to minimize the chances of future accidents. Nevertheless, it is important that the lessons and experience of dealing with situations involving high radiation and high contamination continue to be reported, archived, and shared. This should include, but not be limited to, technology, worker health and safety, management, working with the regulator, and keeping the public informed. These should be addressed by the nuclear safety and radiation protection community, either through amendments of instruments through conventions, new instruments, IAEA General Conference Resolutions, improved guidance, strengthened review services for planning of remediation, and other related actions. Further work is needed for defining acceptable decommissioning strategies (with a focus on end states) and on the design and construction of facilities that may facilitate decommissioning after a nuclear accident. Also, observing that at most sites that have experienced severe accidents, the reactors should be placed in a long-term storage mode to allow for decay, improved technology, and collection of funds. For these cases, it is important to establish disposition pathways for damaged fuel debris and radioactive waste with higher than normal radiation levels and with unusual mixtures of radionuclides and materials.

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The end state of materials, buildings, and sites: Restricted or unrestricted release?

10

T. Hrncir[*,†], M. Listjak[*,‡], M. Zachar[*,†], M. Hornacek[*]
[*]Slovak University of Technology in Bratislava, Bratislava, Slovakia, [†]DECOM, Trnava, Slovakia, [‡]VUJE, Trnava, Slovakia

10.1 Introduction

Peaceful utilization of nuclear energy inevitably leads to the generation of materials containing radionuclides as a result of contamination or the activation process. Concentration of these radionuclides in materials, building structures, or at sites is carefully monitored. In order to protect the health of workers, people living near nuclear facilities, as well as the environment, the fundamental safety principles are jointly issued by the international community. These principles include the following [1]:

- *Optimization of protection*. Protection must be optimized to provide the highest level of safety that can reasonably be achieved.
- *Limitation of risks to individuals*. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.
- *Protection of present and future generations*. People and the environment, present and future, must be protected against radiation risks.

Following the aforementioned principles, the Basic Safety Standards (BSS) were issued jointly by the International Atomic Energy Agency (IAEA), Nuclear Energy Agency/Organisation for Economic Co-operation and Development (NEA/OECD), European Commission (EC), World Health Organization (WHO), and other international organizations. BSS covers all three possible situations [2]:

- planned exposure situations,
- emergency exposure situations,
- existing exposure situations.

The concept of the release of materials, buildings, and sites refers to planned exposure situations. This is in line with the definition of the scope of a planned exposure situation that covers, among other things, the generation of nuclear power, including any activities within the nuclear fuel cycle that involve or that could involve exposure to radiation or exposure to radioactive material [2].

Dose limits for a planned exposure situation are stated [2]; more specifically, the dose limit relevant for the public represents the annual value of 1 mSv. Following the principle of the optimization of radiation safety, dose constraints lower than the aforementioned limit are usually applied for a particular activity; for example, in the case

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of clearance of materials, the effective dose incurred by any individual owing to the cleared material relevant to the reasonably expected scenarios is of the order of 10 μSv or less in a year [2]. This dose level is based on the concept of trivial radiation risk; in other words, the dose is so low that risk related to potential detrimental impact on health is negligible.

These dose constraints should be followed regardless of the planned end state scenarios for material clearance, release of buildings, or sites. Nevertheless, the decision making process leading toward the selection of the end state represents the crucial point in the clearance scenario development and is essential for conducting the safety assessment, as well as deriving the release criteria and related clearance levels.

BSS, as well as many national legislations, stipulate the clearance levels, in other words, concentrations of radionuclides contained in the material, building structure, or site, do not incur a higher effective dose to any individual than the defined dose constraint value; the associated radiation risk is kept at a trivial or negligible level.

These clearance levels are derived according to robust safety assessments, taking into account various possible clearance scenarios. There are available guides issued by the IAEA, EC, or the US Nuclear Regulatory Commission (US NRC) for derivation and justification of clearance levels. However, clearance levels differ from country to country, and this lack of consistency presents a difficulty in this field.

Two concepts are available:

- unrestricted release,
- restricted release.

Concepts vary in the possible further use of the cleared material, released building, or site. Unrestricted release allows any possible further use; in other words, even the reasonable worst-case scenario should be assessed. On the other hand, a specific end state is defined in case of restricted release; in other words, just the selected end state scenario is taken into account. Different exposure pathways and parameters are relevant for each specific scenario. This may have a significant impact on the derived values of clearance levels.

Recently, the release issue became a topic of high importance regarding incentives for waste management optimization and economical effectiveness. Although there are some lessons learned from a few case studies, there is still a lack of experience with restricted release. Similarly, there is a need for consistent guides for both unrestricted and restricted release concepts. This issue was recognized by the IAEA as well as the NEA/OECD.

The IAEA regularly organizes workshops for experts and prepares guides relevant to this issue. Moreover, one of the results of the most recent conference organized by the IAEA in Madrid (May 2016) devoted to decommissioning and environmental remediation activities recommends the development of international standards and guidance for conditional clearance of materials from decommissioning [3].

NEA/OECD is running the projects devoted to the optimisation of the management of (very) low radioactive materials and waste from decommissioning, which include works on the issue related to the management of slightly contaminated materials arising from decommissioning.

The following sections include up-to-date advancements in the process of releasing materials, buildings, and sites. Related basic principles, international recommendations, and guides are gathered, and a brief summary is provided. Available options, as well as case studies relevant for a particular end state of materials, buildings, and sites, are discussed. Moreover, lessons learned from case studies are summarized and benefits or drawbacks connected to particular end state options are outlined. A summary of the chapter includes key findings and ideas that may constitute the basis for wider expert discussion about rationales for using an unrestricted or restricted release approach on a case-by-case basis.

10.2 End state of materials

10.2.1 General principles

The decommissioning of nuclear installations represents a complex process resulting in the generation of large amounts of various waste materials containing different levels of radionuclide concentrations (e.g., very low-level, low-level, intermediate-level, or high-level waste).

The IAEA definition of the waste classes relevant for this chapter are: [4]:

- The very low-level waste classification includes the waste with levels of activity concentration in the region of or slightly above the levels specified for the clearance of material from regulatory control.
- Low-level waste classification is relevant for the waste with activity concentrations higher than the very low level waste, which is suitable for a near surface repository. Low-level waste may contain some level of long-lived radionuclides. An activity concentration limit value of 400 Bq/g on average (4000 Bq/g for a particular package) for long-lived alpha emitting radionuclides is adopted in some states (for long-lived beta and/or gamma emitting radionuclides, the allowable average activity concentrations may be higher and may be specific to the site and disposal facility).

Very low-level waste and low-level waste represent the vast majority in volume of radioactive waste arising from decommissioning. On the other hand, this waste contains only a small fraction of the radiological inventory of a nuclear facility. The concentration of particular radionuclides is so low that some of these materials can be, after application of various techniques, released into the environment. Therefore, selection of an optimal way to manage these materials, taking into account, for example, the concept of clearance, may be vital for a sustainable, safe, and cost-efficient decommissioning process.

Based on BSS, the general criteria for clearance are [2]:

- Radiation risks arising from the cleared material should be sufficiently low as not to warrant regulatory control; there is no appreciable probability of occurrence of scenarios that may result in possible failure to meet the general clearance criteria.
- Continued regulatory control of material would not bring any net benefit; no reasonable control measures would achieve a worthwhile return; in other words, much effort in terms of reduction of individual doses or reduction of health risks would be needed for minimal improvements of an already good situation.

Following the trivial risk principle (the expected dose is so low that the detrimental effect of ionizing radiation is considered negligible), the dose constraint for clearance of materials is defined. Materials may be cleared if the aforementioned dose constraint is met in reasonably foreseeable circumstances of clearance scenarios. The dose constraint value for the clearance of materials is on the order of 10 μSv or less in a year. Addressing the low probability scenarios, a different dose constraint may be used. In this case, the individual effected dose must not exceed 1 mSv in a year.

To facilitate the clearance process, clearance levels valid for unrestricted release of material into the environment were developed and provided in the BSS [2]. Derivation of these clearance levels was performed based on the robust input parameter database and comprehensive analysis of possible scenarios and relevant exposure pathways. In principle, if these clearance levels are met, it is expected that the clearance scenario (even in the case of a worst-case scenario) complies with the release criteria in the form of dose constraint as well, and no further proving or justifying is necessary. Moreover, aforementioned clearance level values were adopted by EC and included in the Council directive 2013/59/EURATOM. All member states must comply with this directive by February 2018 [5]; in other words, this directive represents the next step toward consistency in the field of material clearance in the European Union.

However, an option for development of specific clearance levels is still available. In this case, one must develop a specific clearance scenario, define the end state valid for the scenario, develop the comprehensive database of relevant input parameters, justify the specific input parameters and boundary conditions, conduct the safety assessment specific to the scenario, and prove that specific clearance levels are derived appropriately following the dose constraint principle.

In other words, one must create a robust database and conduct the comprehensive safety assessment relevant for a specific clearance scenario similar to those performed for derivation of clearance levels in BSS. Because different exposure pathways and parameters are relevant for specific scenarios, derived clearance levels for this specific clearance scenario may differ from the clearance levels valid for unrestricted use (specific clearance levels may be less restrictive).

10.2.2 International guides and recommendations

Several recommendations and guides relevant to the clearance of materials are available. The basic documents dealing with the concepts of clearance of materials were issued by the IAEA and EC.

In 2004, the IAEA issued a safety guide devoted to the application of the concepts of exclusion, exemption, and clearance [6]. The basic principles and recommendations were provided. The guide also prescribed values of activity concentration for radionuclides of natural origin as well as for radionuclides of artificial origin in bulk (i.e., clearance levels). Various aspects of applying these values were addressed. The scientific basis and detailed information on derivation of mentioned clearance levels were provided in another document [7]. Clearance levels recommended by the IAEA for unconditional clearance (unrestricted use of materials) were updated via the new BSS [2] in 2014.

The EC issued several documents within the "Radiation Protection Series" devoted to the clearance concept. Two types of materials were considered: metals and concrete rubble. Recommended radiological protection criteria for the recycling of metals from the dismantling of nuclear installations, along with the methodology and models used, are stated in [8,9]. Similarly, two other documents [10,11] were devoted to the clearance of buildings and building rubble, providing related methodology and scientific bases. Specific clearance levels were derived for particular scenarios (restricted use) for metals and building rubble (e.g., clearance values for conditional clearance of metals after application of melting were provided). Council directive 2013/59/EURATOM includes the clearance levels for unrestricted use of materials. However, this directive encourages the Member States to use the specific values and results from analysis done in documents from the Radiation Protection Series.

Besides these guides, robust work was done by the US NRC on radiological assessments for clearance of materials from nuclear facilities [12]. Dose assessments for various scenarios of recycling and disposal of steel, copper, and aluminum scrap, as well as concrete rubble, were done; the rationale for selecting input parameters was also provided.

Moreover, NEA/OECD issued a publication describing advances in the field of release of radioactive materials and buildings from regulatory control in 2008 [13].

Generally, IAEA and EC guidelines recommend the following procedures to develop and justify the clearance scenario and derive relevant clearance levels for considered materials:

1. definition of the end state of particular material—either unrestricted reuse or a particular scenario of restricted reuse;
2. development of the clearance scenario—gathering all necessary input parameters for the scenario (e.g., source term, exposure time, physical parameters, etc.); defining the boundary conditions and particular activities in the scenario;
3. dose assessment—identifying the relevant exposure pathways for particular activities and calculation of effective dose incurred to the critical individual because of the clearance of material and its reuse according to the defined end state;
4. derivation of clearance levels for radionuclides of concern using the results of dose assessment and defined dose constraints.

Although these aforementioned recommendations are available, the regulatory framework for clearance of materials still differs from country to country.

10.2.3 Case studies

The applications of the concepts of clearance depend strongly on the economic, technical, and nontechnical aspects in each country, as well as on the legislative framework. Thus, a general overview providing the status of the application of the clearance concept in selected countries is given in Table 10.1.

Further information of the relevant examples regarding clearance of materials is given in the following sections.

Table 10.1 Clearance of materials in the countries—general overview

State	Clearance concept in the national legislative framework
Argentina	Yes
Australia	No, national protocol
Austria	Yes
Belgium	Yes
Brazil	Yes
Bulgaria	No, separate licensing regime
Canada	Yes
China	Yes
Czech Republic	Yes
Denmark	Yes
Estonia	Yes
Finland	Yes
France	No
Germany	Yes
Greece	Yes
Hungary	Yes
Ireland	No
Japan	Yes
Poland	Yes
Romania	Yes
Slovakia	Yes
Slovenia	Yes
South Africa	Yes
Spain	Yes
Sweden	Yes
United Kingdom	Yes
United States	Yes

10.2.3.1 Belgium

Practical experiences in clearance of materials is from the decommissioning process of a small pressurized water reactor BR3 (electrical output 10.5 MW, operation in 1962–87) and open pool research reactor Thetis (power of 150 kW, operation in 1967–2003). In the case of both reactors, more than 90% of the materials are clearable (92% from Thetis and 91% from BR3) [14].

Another example is decommissioning of a former reprocessing plant Eurochemic (site BP1), which was in operation from 1966 to 1974. From the start of decommissioning in 1989–2014, 1239 tons of metallic materials were released into the environment for unrestricted use (about 70% of the entire metal inventory). This involved segmentation, blasting, and melting of the metals [15].

10.2.3.2 Czech Republic

An example of clearance of materials is from the activities connected with remediation of environmental liabilities in ÚJV Řež, a.s., where all RAW stored at the storage area Červená skála was removed. In total, 4377 kg of waste material has been cleared; another 16,250 kg of this material has already been monitored for compliance with clearance levels and is ready for unconditional clearance [16].

10.2.3.3 Denmark

The clearance measurements are carried out in F-lab, which is situated in the same area where the other nuclear facilities are located (on the Risoe peninsula to the north of Roskilde). F-lab deals with the materials arising from the decommissioning of DR 1 (Danish Reactor 1), DR 2, DR 3, Hot Cell Facility, and Fuel Fabrication Facility. From October 2011 to October 2014, a total mass of 167 tons of material has been released from regulatory control [17].

10.2.3.4 Germany

Because of the current lack of final disposal options for radioactive waste, Germany has a well-developed concept of clearance of materials. To meet the requirements for release of the materials from regulatory control, the following operations can be carried out [18]:

- Storage (e.g., in Interim Storage North at Greifswald site)—decay storage. However, this approach is very sensitive to possible change of the clearance limits.
- Decontamination (e.g., in a central active workshop located in a separate building at the Greifswald site).

Examples of clearance of materials are listed as follows [19,20]:

- Nuclear Power Plant (NPP) Greifswald—a total amount of cleared material of about 94,000 tons (about 26,000 tons of concrete and 68,000 tons of plant components).
- NPP Stade—from 132,000 tons of materials from nuclear area:
  - 97.3% (128,500 t) controlled release;
  - 0.4% (500 t) controlled reuse and recycling;
  - remaining 2.3% (3000 t)—radioactive waste.

Besides the chemical and mechanical decontamination techniques, the decontamination of the metals can be realized by melting technology as well. In Germany, this is carried out in the CARLA melting facility. From 1989 to 2009, 25,000 tons of metal were processed, 9000 tons could be cleared, and 14,500 tons were recycled within the nuclear industry (e.g., for production of shielding) [21].

In the German legislative framework, eight clearance options are defined; four options are available for the unconditional clearance [18]:

- unconditional clearance of (solid or liquid) substances that may later be reused, recycled, or disposed of;

- unconditional clearance of rubble and excavated soil of more than 1000 Mg per year that after clearance may be used for any chosen purpose, for example, for the backfilling of excavations, such as road bedding, etc.;
- unconditional clearance of buildings that afterwards may be demolished or also be reused;
- unconditional clearance of soil areas that may subsequently be used for any purposes, for example, for the construction of houses and apartment buildings, industrial buildings, etc.

In the case of clearance for a specific purpose, in other words, conditional clearance (in which the first step is exactly specified) has four clearance options [18]:

- clearance of solid substances for disposal in a (conventional) landfill with masses of up to 100 Mg/a and up to 1000 Mg/a, respectively;
- clearance of (solid or liquid) substances for removal in an incinerator with masses of up to 100 Mg/a and up to 1000 Mg/a, respectively;
- clearance of buildings for demolition, with any conventional use of the buildings prior to their demolition being impermissible;
- clearance of scrap metal for recycling by smelting in a conventional melting facility, for example, foundry, steel works, etc.

10.2.3.5 Slovakia

Slovakia has several projects where the clearance of materials is carried out. An example is the clearance of underground tanks at A1 NPP in Jaslovske Bohunice (former tanks for CO_2). In this case, about 735 tons of metals can be released to the environment [22]. Another example is unrestricted release of concrete underground tanks at A1 NPP site, which were then filled with clean soil [23]. During the decommissioning process of underground tanks, bulk volumes of slightly contaminated soil were excavated. Based on the measurement conducted at a special facility (as shown in Fig. 10.1) the decision was made whether the soil meets the clearance limits or should be disposed of at repository for very low-level radioactive waste.

Fig. 10.1 Facility for measurement of contaminated loose materials.

Similarly, the significant amount of cleared materials can be expected during ongoing decommissioning of V1 NPP in Jaslovske Bohunice.

10.2.3.6 Sweden

The metallic radioactive waste can be treated in the melting facility of Studsvik (operated from 1987). Until 2014, about 27,700 tons of scrap metal (carbon and stainless steel), 800 tons of aluminum, and 400 tons of lead were treated [24]. Examples of the quantities of cleared materials [24,25] were provided, as follows:

- 600 tons in 2004 cleared for disposal at municipal landfills;
- 764 tons of melted metal cleared for recycling in 2010;
- approximately 10,000 tons of ingots cleared for restricted use produced from 2005 to 2012.

10.2.3.7 France

According to French legislation, the recycling or reuse of materials, even if very slightly radioactive, is allowed exclusively in the nuclear industry (waste containers, biological shielding in waste packages, etc.). This law means large quantities of materials that cannot be cleared are generated and must be disposed of as radioactive. Therefore, the concept of disposal of very low-level waste has been developed, and the repository in Morvilliers is used for this operation.

French legislation prescribes the zoning approach; that is to say, waste zoning is implemented within nuclear installations in order to segregate areas where waste cannot a priori be contaminated or activated and areas where waste contains or may contain added radionuclide concentrations. This approach has several benefits, but it also has a major drawbacks.

Benefits include [20]:

- no dissemination of radioactivity into the environment due to the management of large amounts of very low-level waste;
- easier to put in the practice for decommissioning—no sophisticated measurements are needed for the clearance of materials;
- practical way to dispose of very low-level waste that does not meet clearance levels.

The main drawback of the concept is that it makes it difficult to clearly define whether the materials are radioactive or conventional (nonradioactive). Moreover, this concept may not be suitable for countries with small or developing nuclear sectors. Although only few nuclear installations are located in these countries and lower quantities of very low-level waste are expected, the requirement to have sufficient disposal capacity (often significant volumes are necessary) for very low-level waste represents a challenging issue.

10.2.4 Discussion

As it was mentioned earlier, recommended clearance values enabling the unrestricted reuse of materials are available. Moreover, thanks to the Council directive, the next step toward consistency in the field of unconditional clearance of materials already exists at least in the European Community.

However, there is still a lack of consistency in the clearance concept, and the legislative framework for clearance differs from country to country. Moreover, there are only a few examples of utilization of the conditional clearance concept (e.g., application of metals clearance after melting in Germany). Conditional clearance seems to be interesting from the economic point of view and may lead to optimization of the use of disposal capacities. Although principles for derivation of specific clearance values are well known, and procedures for derivation are available in the guides, it would be useful to update these guides (many of them were issued more than 10 years ago). Furthermore, guides focused particularly on conditional clearance may be beneficial, especially for countries with limited budgets and with a lack of waste disposal capacities.

Following the waste management hierarchy, disposal as radioactive waste should be the last option. The application of different approaches leading to optimization of waste management is highly desirable from a sustainability and economic point of view. The clearance of materials, both for restricted (conditional clearance) and unrestricted (unconditional clearance) use, along with recycling of materials or equipment, represents a promising option, keeping in mind the required level of safety.

Because a particular scenario is assessed in the case of conditional clearance, higher specific clearance levels may be achieved. However, much effort is required to develop the safety case for a particular scenario, derive the specific clearance levels, and analyze the impact on the waste management system, including the optimization of the use of disposal capacities. Moreover, the overall assessment of a particular conditional clearance scenario should address the economic aspects in order to prove that scenario is feasible and that would provide a worthwhile return.

Another option is recycling and reuse of the materials and equipment within the nuclear sector. Application of this process may save significant financial resources. In the United Kingdom, the Nuclear Decommissioning Authority created an asset transfer scheme in order to advertise unwanted items or seek redundant equipment from other nuclear sites. Reusing and recycling across the Nuclear Decommissioning Authority's estate is expected to save £15 million over 8 years [26].

Guides covering the economic aspects and other nontechnical aspects (e.g., stakeholder involvement) of the conditional clearance or recycling of materials within the nuclear sector would be useful as well.

Alternatively, disposal of slightly contaminated materials at the repository for very low-level waste is preferred in some countries in order to avoid complex clearance procedures and verification of compliance with clearance criteria.

Therefore, a detailed study addressing the safety, technical, and economic aspects of particular options is crucial for the selection of the optimal option for the management of materials containing very low concentration of radionuclides.

10.3 End state of buildings

10.3.1 General principles

The selection of a particular end state of buildings has a significant impact on their release criteria. Possible principal end state options are the following:

- demolition of buildings;
- release of buildings for unrestricted purposes;
- release of buildings for restricted purposes.

In the case of planned building demolition, it is necessary to bear in mind that generated building rubble is movable material, and thus the rubble should comply with the criteria valid for material clearance. In other words, the effective dose for an individual valid for reasonably foreseeable circumstances of clearance scenarios is of the order of 10 μSv or less in a year (see general principles for materials clearance for further details).

However, if it is planned that building structures remain standing at the end of decommissioning, it is possible to treat these buildings as a part of the site to be released. This means that it is possible to apply the site release criteria and include the residual radioactivity contained in the building structures to the site source term. Based on the IAEA recommendations, the dose constraint valid for release of the site is up to 300 μSv in a year (for further details, see general principles for site release) [27].

10.3.2 International guides and recommendations

There are a few guides addressing the steps in the release of buildings, as well as the derivation of clearance levels. EC issued several documents within the radiation protection series. Two documents [10,11] were devoted to the clearance of buildings and building rubble and related methodology and scientific bases. Specific clearance levels were derived for three scenarios relevant for building release [10,11]:

- *Reuse of buildings*. After the clearance process, the buildings can be used for nonnuclear purposes or be demolished; the clearance level was expressed as the total activity in the structure per unit surface area (the typical process of the final radiological survey along with the measurement mesh is depicted in Fig. 10.2).
- *Demolition of buildings*. Buildings are demolished resulting in the generation of rubble; the clearance level was expressed as total activity in the structure per unit surface area;
- *Specific clearance criteria for building rubble*. The clearance level was expressed as mass-specific activity.

Another useful guide is the Multi-Agency Radiation Survey and Assessment of Materials and Equipment manual (MARSAME) [28]. MARSAME is a supplement to the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) [29] and provides a detailed approach for planning, performing,

Fig. 10.2 Development of a measurement mesh for the purpose of building a final radiological survey.

and assessing disposition surveys of materials and equipment, while at the same time encouraging an effective use of resources. This approach is often used in the United States.

10.3.3 Case studies

The following case studies may illustrate the possible end state options for the release of buildings from regulatory control.

10.3.3.1 Germany—Greifswald

At the Greifswald site, eight Russian pressurized water reactors were either in operation or planned to operate. Five operating reactors were shut down in 1989 and 1990; one unit was ready for commissioning, and the buildings were erected for two others and major components were installed. The overall objective of the decommissioning project was to dismantle the main components, remove radioactive legacies, and remediate the area to allow its further industrial reuse (more in Section 10.4.3). No complete demolition of all buildings was performed; subsequent release for restricted purposes (industrial reuse) of many of the buildings took place. The most significant example of reusing the buildings for nonnuclear purposes is the former turbine halls. The equipment of both turbine halls was dismantled and the buildings were prepared for industrial use [30–32]:

- turbine hall for Units 5–8 are used for manufacturing of large ship components and parts of the offshore wind mill farms;
- turbine hall for Units 1–4 are used for manufacturing of large maritime cranes.

10.3.3.2 Slovakia—A1 Nuclear Power Plant

A1 NPP represents the Heavy Water Moderated Gas Cooled Reactor (HWGCR) with the output power 150 MW, which ended operation after an accident in the 1970s. Currently, the NPP is in the decommissioning phase. Some auxiliary buildings have already been demolished — areas remain as a part of the nuclear site. The buildings, which are suitable to be reused for the construction and operation of waste treatment and conditioning technologies (including the main production unit with the reactor building and turbine building), are currently planned to be reconstructed and later on to be included into the existing nuclear facility called Radioactive Waste Processing and Treatment Technology. This means that after the end of the A1 NPP decommissioning project, some buildings will be reused for restricted purposes within the nuclear industry [33].

10.3.3.3 United States—Complete demolition of buildings from NPPs

There are several examples of nuclear power plants in the United States (e.g., Connecticut Yankee, Yankee Rowe, Maine Yankee) that shut down in the 1990s, and they were decommissioned by applying the strategy of immediate dismantling [34–36]. The achieved end state of all the buildings was their complete demolition (including relevant infrastructure). This was done by using explosives as well as conventional demolition methods.

10.3.4 Discussion

Similar to the clearance of materials, international guides are available for the release of the buildings. However, one can identify the same issues as in the case of guides for materials release:

- These guides may need updating, since many of them were published more than 10 years ago; it would be useful if updates include more information particularly devoted to the restricted release scenario.
- Lack of consistency in the release process. However, the degree of certainty of possible further use of buildings (sites) is higher than in case of materials, which may be transferred from country to country. Therefore, the consistency issue is more pertinent in the case of materials clearance.
- Guides covering the economic and other nontechnical aspects, particularly for the restricted release scenario, may be beneficial.

The selection of the end state of the buildings is critical, since it may have an impact even on the annual dose constraints applied in the release process (10 μSv for rubble or 300 μSv for buildings remaining at the site). Therefore, a detailed study addressing the safety, technical, economic, and other relevant aspects of particular options is highly desirable in order to select an optimal end state option.

In the case of planned demolition of the building, one should take care to observe the level of contamination. It is not considered to be good practice to demolish building structures with a higher level of contamination in order to mix the surface contamination with the uncontaminated interior of the building structure. Clearance of resulting rubble (using the mass-specific clearance levels) is considered intentional dilution and generally rejected by regulators. Therefore, the surfaces of such highly contaminated structures should be removed before demolition, and the resulting concrete rubble should be treated as radioactive waste [11].

These case studies present the potential for reuse of the buildings mainly for restricted industrial purposes. The early release of the buildings from regulatory control may generate revenues to finance the cost of other necessary work on site.

10.4 End state of sites

10.4.1 General principles

As in the case of clearance of materials and buildings, dose limitation and optimization of protection approaches also is applied for site release. Identification of exposure pathways in the case of site release is more complex, and multiple pathways of exposure should be taken into account. The annual dose constraint for the release of site is 300 μSv above background dose. Based on the IAEA recommendations, it is reasonable and appropriate to have different dose constraints for the release of sites than for the clearance of material from regulatory control. The rationale for the considerations is as follows [27]:

- clearance of materials may occur frequently;
- cleared materials may easily spread, even transboundary movement of materials may occur;
- land remains in place and thus the degree of certainty about the potential uses of the land (similarly about the identification of critical group) is higher than in the case of materials clearance.

The visualization of the concept of dose limitation and optimization is illustrated in Fig. 10.3.

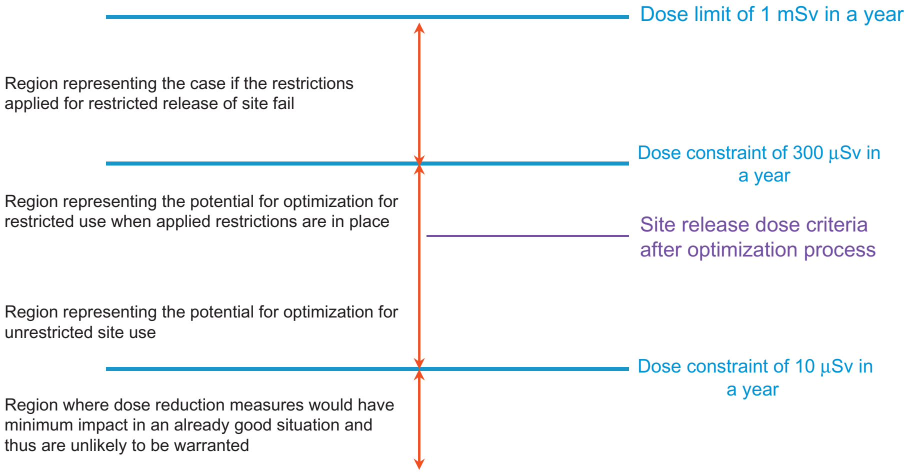

Fig. 10.3 Dose limitation and optimization relevant for the process of site release [27].

Basically, there are many end-state options valid for sites: for example, unrestricted use, natural reservation, use of the site for industrial purposes, turning the site into a disposal site, or long-term stewardship of the site. In the case of restricted release of site, the idea is to set some restrictions (e.g., restricted access leading to decrease of the possible exposure time of individuals) ensuring that the dose constraint of 300 μSv in a year will be met with restrictions in place, or if the restrictions were to fail in the future, the dose limit of 1 mSv in a year will not be exceeded.

10.4.2 International guides and recommendations

Similar to a previous case, the process of selection of the appropriate end state of the site and further use of land is crucial in the site release procedures. Redevelopment of the land (nuclear site) requires that the land be remediated to residual levels of contamination that are in compliance with its intended use. It is likely that, in many nonaccident scenarios, only restricted release of a nuclear site will be feasible, hence the stewardship process will need to cover the management of the future land use [37].

In most countries, different national agencies are involved in the decommissioning processes and are responsible for the release of sites following cleanup. To provide consistent guidance and the best practices to stakeholders, important documents have been published by different organizations, including:

- International Atomic Energy Agency Safety Guides and technical reports;
- SAFEGROUNDS Learning Network, which uses participatory approaches to develop and disseminate good practice guidance for the management of contaminated land on nuclear and defense sites in the United Kingdom;
- Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM).

The different approaches caused by the various missions of these organizations can be recognized in their documents.

MARSSIM provides information on the planning, conducting, evaluating, and documenting of building surface and surface soil final status radiological surveys for demonstrating compliance with dose or risk-based regulations or standards. MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil final status surveys to meet established dose or risk-based release criteria, while at the same time encouraging an effective use of resources [29].

Robust guidance in this field is provided by the Environmental Radiation Survey and Site Execution Manual (EURSSEM), developed by EC's Co-ordination Network on Decommissioning of Nuclear Installations. EURSSEM incorporates information provided in the documents of these organizations and acknowledges the importance and the quality of the information and know-how presented in their documents. It was developed as consistent guidance for environmental remediation projects [37].

EURSSEM consists of five major sections [37]:

- *Section 1*: Introduction, purpose, and scope. The EURSSEM manual has been developed to provide a consistent consensus approach and guidance to conduct all actions at radioactively contaminated and potentially radioactively contaminated sites and/or groundwater up to their release for restricted or unrestricted (re)use.
- *Section 2*: Development of a strategy, implementation, and execution program to remediate radioactively contaminated sites. This section deals with the development of a remediation program, which requires sound knowledge of the necessary plans and topics involved in each of these plans.
- *Section 3*: Characterization of radioactively contaminated sites. The section is devoted to all the aspects of the planning and executing characterization as well as the analysis, validation, and interpretation of collected data and drawing conclusions.
- *Section 4*: Environmental remediation of radioactively contaminated sites. This section provides detailed guidance on the design of environmental remediation plans, approaches, and an overview of remediation techniques applicable for radioactively contaminated sites and/or groundwater.
- *Section 5*: Stewardship is aimed to present detailed guidance for stewardship: for example, when to implement, what plans/actions should be carried out, etc.

10.4.3 Case studies

Naturally, the concept of release of sites strongly depends on the technical and non-technical aspects, as well as available legislative framework. Moreover, the involvement of stakeholders plays an important role in the selection of appropriate end state of the particular site. The large variety of possible end states is outlined via the following several case studies.

10.4.3.1 Germany—Fuel assembly plant, Hanau

Fuel assemblies for research reactors and high-temperature reactors were developed and produced at the former fuel assembly plant in Hanau. In 1988, all physical development and production activities were stopped. Permission for decommissioning according to the German Atomic Energy Act was granted in 2000. The first step within the decommissioning process was the decommissioning of the components and the demolition of the buildings. Soil remediation started in 2001, and groundwater remediation started in 2002. Full release of the site was the only possible end state of decommissioning of the facility and remediation of the site. In other words, the concept of 10 μSv as a maximum dose per year to any concerned member of the public had to be met. This fact led to the conclusion that unrestricted use (except direct agricultural use of the area) was considered. No options for restricted reuse and no options for other dose criteria were taken into account in the evaluation of possible site reuse [38].

10.4.3.2 Germany—Greifswald Nuclear Power Plant

From the beginning of the Greifswald decommissioning project (more in Section 10.3.3), the restricted reuse of the site for industrial and energetic purposes was considered within the decommissioning concept, into account taking the advantages from the existing infrastructure (electrical grid connections, rail systems suitable for complete trains, roads) and qualified personnel available at the site. The industrial area with a size of 120 ha was established after performing the release measurements aimed to release the relevant areas from regulatory control. The following activities were implemented at the Greifswald site [30,31]:

- reconstruction of the outlet channel of the NPP to industrial harbor;
- improvement of the infrastructure (roads, rails, installation of a new high-voltage switch yard);
- refurbishment of former turbine halls after complete dismantling (more in Section 10.3.3);
- settlement of different private (industry and energy) companies at the site (outside of former NPP buildings)—solar power plant, gas power plant, offshore wind farms, biodiesel factory, gas distribution station.

Moreover, the building for interim storage of spent fuel (dry storage in metal casks), large components of the primary circuit (reactor pressure vessels or steam generators), radioactive waste in the various overpacks, as well as for establishment of facilities for cutting, treatment, or conditioning of solid and liquid radioactive waste from decommissioning was constructed at the site. In other words, the Greifswald site is still used for nuclear purposes as well.

10.4.3.3 Canada

Final end states of the sites after termination of decommissioning or remediation activities in Canada are determined on a case-by-case basis. For example, NEA/OECD [38], Voight and Fesenko [39], Aikens [40], and IAEA [41]:

- *White Shall Laboratories* (reuse of the site within nuclear industry): Established in 1963; consists of a number of nuclear and nonnuclear facilities, including WR-1 and heavy water moderated reactor (currently in storage with surveillance). In 2003, the site received approval of an overall decommissioning framework. Since that time, redundant nuclear and nonnuclear buildings have been demolished, enabling the development of nuclear-based industries at the site—construction and operation of new nuclear facilities for decommissioning waste retrieval, characterization, handling, clearance minimization, and storage (e.g., Shielded Modular Above-Ground Storage Facility).
- *Chalk River Laboratories* (restricted industrial reuse): Complex of almost 500 buildings and structures (including five research reactors), many of them still in operation. According to the Comprehensive Preliminary Decommissioning Plan for the Chalk River Site, the planned and ongoing decommissioning activities are aimed to achieve the final long-term goal of the site. Formerly controlled areas are reused for industrial purposes, taking advantage of the infrastructure or management arrangements at a nuclear site.
- *Port Hope area* (unrestricted reuse): Residues from radium refining were placed at several locations in/around the Port Hope area. Other areas were contaminated through a variety of other ways. Following the extensive public consultation program, the development of an improved long-term storage facility for the contaminated materials and soils remaining in the interim storage facility enabled additional remediation in the area. The planned end state of the contaminated site is reuse for unrestricted purposes.

- *Elliot Lake* (converting a nuclear site into a waste-disposal facility): Former uranium mine and milling complex that closed down in the 1990s. Decommissioning of the site involved the dismantling of all infrastructure and release of metals, where possible, for recycling. The materials that could not be cleared were placed either in some of the underground workings or in the surface landfills along with other contaminated materials, waste rocks, and tailings. Contaminated soils were placed either inside the mine working (underground landfilling) along with the building rubble or in the surface landfills. All mine openings were capped and comprehensive environmental monitoring programs were applied.

10.4.3.4 United States

For the examples of US nuclear power plants (e.g., Connecticut Yankee, Yankee Rowe, Maine Yankee), mentioned in Section 10.3.3, the greenfield status of the sites (i.e., unrestricted release of sites) was finally achieved after the end of all decommissioning works. Only areas of interim spent fuel storage remain on or near the former NPP sites, and they are still under the license of the US NRC. The remaining areas were released for further unrestricted reuse, but the decision about the future use of the sites has still not been finalized [34–36].

10.4.3.5 Slovakia

Following current legislation in Slovakia, release criteria for the clearance of materials are the same as for the release of sites (the same 10 μSv dose constraint is applied). In the case that a radiological survey (both measurements and soil sampling) identifies contamination with a concentration of radionuclides higher than defined clearance levels, the excavation of soils is required. Considering the penetration of contamination into the deeper zones of soil and relatively strict release criteria, the extent of excavation at the Jaslovske Bohunice site was much larger than initially expected (maximal depth of excavation was 1.8 m below ground). Lessons learned from the release of a small part of the Jaslovske Bohunice site show that application of the strict material clearance criteria for the site release leads to unnecessarily high costs for verifying compliance with the clearance criteria and relevant corrective measures [42].

10.4.4 Discussion

Although robust guides relevant for the release of sites are available, there is still a low level of consistency in this field. Some countries applied the 10 μSv dose constraint, while legislation of some countries allows higher values, up to 300 μSv in a year. Generally, the release levels for unrestricted use may be applied or site-specific release criteria may be derived, keeping in mind the dose constraint principle. Moreover, some countries follow MARSSIM or EURSSEM methodology for a radiological survey to create a survey (measurement or sampling) mesh with a statistically sufficient number of points depending on the potential contamination data. On the other hand, the legislative framework of some countries required 100% covering of the site (e.g., one measurement for each 1 m^2) during radiological surveys, proving compliance with the site release criteria. The final radiological survey within the

Fig. 10.4 Measurement and sampling of soil for the purposes of the site's final radiological survey.

site release process, particularly the measurement and sampling of soil at the site, is illustrated in Fig. 10.4.

Generally, the early release of the site or part of the site may generate revenue to cover, at least partially, the cost of the other required activities: for example, necessary institutional control, further remediation activities, or continuing dismantling [37,41].

As it was stated in the previous sections of this chapter, selection of the end state is a vital part of the release process. Based on the international recommendations, the stakeholders should be involved in the process of end state selection at an early stage in order to enhance the communication process and build trust. A discussion with the stakeholders and an explanation of various aspects of particular end states is crucial, since the stakeholders, particularly members of public, often desire unrestricted reuse of the land. However, sometimes this option may not be easily achieved and selection of too-strict release criteria may make the release process significantly more difficult and costly.

Unnecessarily strict criteria may sometimes lead to minimal improvement of an already good situation in which the enormous effort connected to the site release process (e.g., significantly increased costs, generation of large quantities of waste, etc.) would not be worthwhile.

A good example for illustrating of possible impact of strict criteria may be remediation activities after accident in Fukushima. In Fukushima, remediation efforts have been aimed to reducing the dose rates and encouraging people to return to the less-affected areas. The public desired the unrestricted reuse of the land. Remediation activities resulted in the generation of enormous quantities of very low-level and low-level waste. This became a problem from a disposal point of view. Therefore, in the stage of end state selection, it is crucial to bear in mind the overall life cycle management, not to be focused only on one stage [43].

Finally, it is important to note that dose constraint is 300 μSv in a year above background. Therefore adequate selection of background concentration of particular radionuclides plays important role in the process of site release.

10.5 Conclusions

Generally speaking, several comprehensive documents are available for the clearance of materials and release of buildings and sites. However, the majority of these documents were issued more than 10 years ago; thus some updating would be desirable. Moreover, it would be useful, particularly for developing nuclear countries and for countries with limited budgets, to develop guides addressing the following:

- safety and technical aspects of derivation of specific clearance levels or release criteria;
- economic and other nontechnical aspects of both unrestricted and restricted release;
- case studies and lessons learned from the application of the concept of restricted release.

The abovementioned guides may contribute to the harmonization of the release process. As it was mentioned, a significant step leading towards harmonization was made by publication of the IAEA Basic Safety Standards [2] and the Council directive 2013/59/EURATOM [5]. However, much effort will be required to achieve the desired level of consistency.

Following several case studies on conditional clearance of materials and restricted release of buildings and sites, these concepts may save financial resources, may be vital for the optimization of waste management (particularly for very low-level and low-level waste), and may contribute to the overall effectiveness and sustainability of the decommissioning processes. Furthermore, it is necessary to take into account the principles of lifecycle management, in other words, not to focus only on one stage of the overall process.

A notable case study is the application of conditional clearance of metals after melting in Germany. German national legislation adopts specific clearance levels relevant for the clearance of materials after melting in a commercial melting facility. In this case, interested parties developed the particular scenario, made an agreement with the regulatory body, and built a sufficient level of trust for acceptance of slightly radioactive materials by the commercial melting facility. The result is that both the NPP operator and owner of the melting facility benefited from application of the conditional clearance concept.

Nevertheless, application of the concept of restricted release requires development of a safety case, gathering information, developing a comprehensive database of relevant input parameters, performing the dose assessment, deriving the release criteria, determining the methods for verification of compliance with release criteria, and assessing economic and other relevant aspects. This requires involvement of highly qualified experts in order to develop an analysis (applicant side) and to review these analyses (regulatory body side).

A high level of constructive and open discussion with the regulatory bodies and further communication with the stakeholders involved may create basis for wider application of the restricted release concepts, keeping in mind the required level of safety for the population and the environment.

Naturally, if unrestricted release is reasonably practicable or achievable, this option should be preferred. However, strictly defined release criteria and following the unrestricted release option without taking into account the economic aspects may result in an unnecessary increase of costs, rapid decrease of available disposal capacity, or other issues (see the Fukushima example in Section 10.4.4).

This inevitably leads to the principal question: “How clean is clean?” In other words, one should analyze whether a little improvement of an already good radiological situation is worth making a great deal of effort in terms of protective measures for achieving radiological improvement. This questioning attitude may help to find the optimal solution.

To conclude, many specific technical and nontechnical issues still should be addressed and agreed upon. The necessity for new or updated guidelines has been recently recognized by both the IAEA and NEA/OECD. The IAEA regularly organizes workshops for experts and prepares guides relevant to this issue. Moreover, one of the goals of the most recent conference organized by the IAEA in Madrid was the development of international standards and guidance for conditional clearance of materials from decommissioning [3]. Similarly, NEA/OECD is running projects devoted to the optimization of the management of very low radioactive materials and waste from decommissioning, which include works on the management of slightly contaminated materials arising from decommissioning process.

Hopefully, these ongoing activities may create a framework and a solid knowledge basis for other countries to consider various options for optimization of waste management, including use of both restricted and unrestricted release concepts.

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Part Three

International Experience

Recent experience in decommissioning research reactors

11

K. Lauridsen
Consultant, Roskilde, Denmark

11.1 Introduction

Worldwide there are large numbers of research reactors of different types and sizes, varying from the size and complexity of power reactors down to small facilities on a laboratory scale. Power levels vary from a few watts to more than 100 MW. Also the inventory of radioactive material may have a broad range, including the activated reactor construction material and shielding, as well as radioactive material contained in stored spent fuel elements, radioactive waste from radioisotope production, and various types of active experimental facility.

The designs of research reactors vary considerably, although there are some types that exist in larger numbers worldwide, such as the Argonaut (Argonne Nuclear Assembly for University Training), the TRIGA (Training, Research, Isotopes, General Atomics), and the Russian VVR (or WWR—water-cooled and moderated reactor). Depending on the planned application these types have come in a number of layouts.

Research reactors are used for a wide range of activities such as core physics experiments, training, transmutation studies, commercial production of radioisotopes, neutron activation analysis, experiments involving high pressure and temperature loops for fuel and material testing, neutron scattering research, and neutron and gamma radiography. In the early days a number of research reactors also played a role in the development of nuclear weapons.

Many, if not most, research reactors are more than 50 years old and are approaching the end of their operating lives and will require decommissioning. Although the radioactive source terms within research reactors are expected to be less in radioactive inventory than in larger facilities, they may still pose significant radiological and other risks, due to aging and other issues resulting from the experimental character of their use. Furthermore, many organizations decommissioning a research reactor have experienced that their reactor was not "designed with a view to being decommissioned."

According to the IAEA Research Reactor Database [1] there were by Aug. 2016 244 operational research reactors in 55 countries; more than 150 that have been shut down or are undergoing decommissioning, and more than 350 that have been fully decommissioned. Many of those decommissioned have been small facilities that were shut down and decommissioned many years ago without much reporting in public. However, in recent years more information has been published about completed

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decommissioning projects of research reactors, notably thanks to the efforts of the International Atomic Energy Agency (IAEA) and dedicated journals.

In Sections 11.2 and 11.3 of this chapter, examples are given of decommissioning projects in order to highlight special or common aspects, such as selection of strategy, end state, and general technical approaches to the dismantling project. Elements gathered from individual reactor decommissioning experiences are summarized in Section 11.4.

11.2 Ongoing or recently completed decommissioning projects

This section does not intend to mention all projects covered by the heading. But examples will be given of projects where published material has been available, and only particular aspects of each individual project will be discussed. References will be given to sources of further information about the projects mentioned.

11.2.1 Danish Reactor 2

The Danish Reactor 2 (DR2) was the second out of three research reactors to be decommissioned at the Risø site in Denmark. The first one was the small 2kW DR1 that was decommissioned in 2006. DR2 was an open-tank, light water moderated and cooled reactor with a thermal power of 5MW. The reactor went critical for the first time in Dec. 1958 to be used mainly for isotope production and neutron scattering experiments. It was shut down in Oct. 1975 for economic reasons and partially dismantled. All experimental facilities were dismantled, the spent fuel elements were shipped back to the United States, and the reactor block and the cooling system were sealed. Subsequently the reactor hall was used for other purposes until 1997, when a predecommissioning study was initiated in order to benefit from the fact that some members of the former operational staff were still available to contribute historical information. This study resulted in a characterization report [2], which gave the background information for the detailed decommissioning planning that was initiated in 2004 after the responsibility for decommissioning of the facilities at the site had been transferred from Risø National Laboratory (RNL) to Danish Decommissioning (DD). DD is a state organization with a budget that is independent of RNL's research budgets; this has been seen as an advantage, avoiding any prioritization between research and decommissioning. Most of the original DD staff was staff from the research facilities, but over the years many new staff members have come from outside the site, bringing in new competences.

Decommissioning of the DR2 was completed in 2008; the reactor building was cleared and left for other purposes. Fig. 11.1 shows a cross-section perspective of the reactor in the building as it appeared when the final decommissioning was initiated.

Selection of dismantling methods started when the first overall plan was drafted for decommissioning of all nuclear facilities at the site [3]. More detailed planning was made in the decommissioning plan for DR2 put forward for approval by the nuclear regulatory authorities and when setting up the budget to be approved by the Parliament's Finance Committee. But the selection of precise approaches and tools to be used in the individual dismantling operations to some extent was made during the detailed preparation of

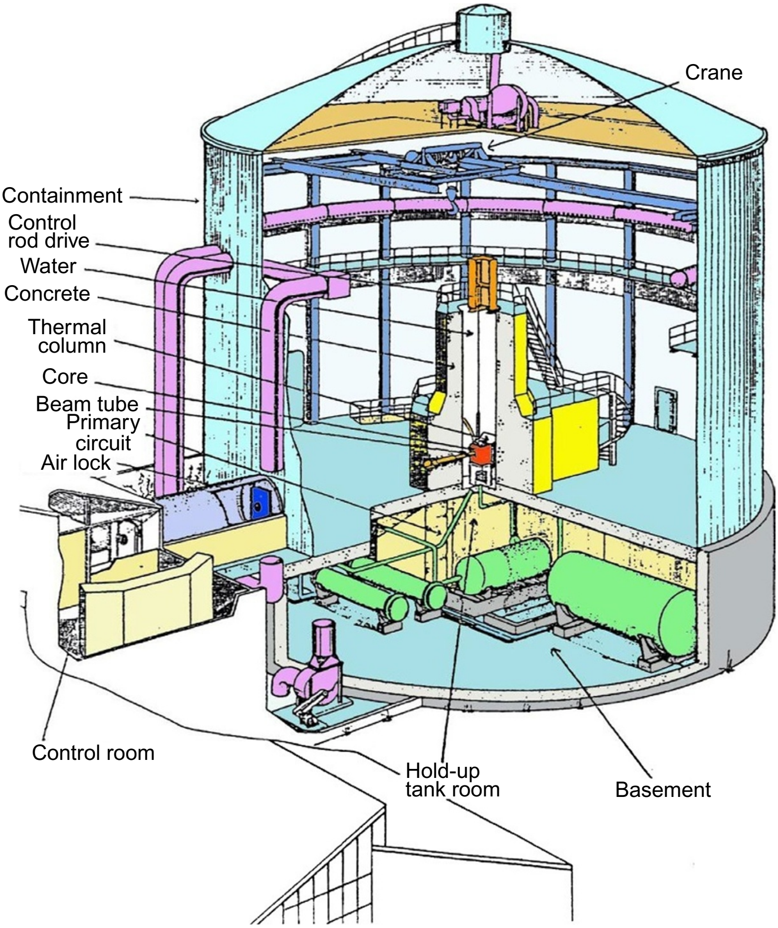

Fig. 11.1 Cross-section perspective of reactor DR2 in the building.
From N. Strufe, 2009. Decommissioning of DR2. Final report. DD-38 Rev.1 (ENG). Danish Decommissioning, Roskilde. Available as a PDF-file from the Internet address: http://www.dekom.dk/media/24133/dr%20dr2_%20final%20report_eng.pdf.

these operations. The general approach by DD is to do as much of the dismantling of active components as possible with its own staff and only to call in external contractors for work that involves little or no radioactivity. This was also the case in the DR2 project where external contractors essentially were used only for concrete demolition.

Because the reactor had been shut down for 30 years when the final dismantling started the radiation levels and activity contents were moderate. The highest radiation levels were of the order 40–50 mSv/h and came from steel pins in the fuel grid plate and thermocouples in the front plate of the thermal column. Dismantling thus did not require the use of remote handling techniques, apart from using extension rods for tools in certain cases, such as shown in Fig. 11.2 where the operator, using a plasma cutter mounted on a long rod, can keep a distance of a couple of meters to the radiation source.

Fig. 11.2 Nose of thermal column being cut loose with a plasma cutter on an extension rod. From N. Strufe, 2009. Decommissioning of DR2. Final report. DD-38 Rev.1 (ENG). Danish Decommissioning, Roskilde. Available as a PDF-file from the Internet address: http://www.dekom.dk/media/24133/dr%20dr2_%20final%20report_eng.pdf.

The inner part of the graphite in the thermal column turned out to have accumulated some Wigner energy, and it was decided that the graphite stringers were to be annealed from the inner layer at a later stage, possibly together with graphite from the next reactor being decommissioned, DR3.

Additional characterization was performed in order to determine how much of the biological shielding should be considered radioactive waste and how much could be cleared as ordinary industrial waste. Twenty horizontal core drillings were made in the shield and used to determine the activation profile. As a result the innermost 100 cm, as illustrated in Fig. 11.3, was considered radioactive waste; that is, it above the mass specific clearance levels set by the Danish regulators.

Initially it had been planned to demolish the biological shield by dry wire cutting; DD had had a less positive experience with wet wire cutting at the DR1. But demolition by hydraulic hammering was found to be the more economical solution, and the separation of radioactive and clearable concrete was still possible.

A detailed description of the decommissioning of DR2 can be found in the final decommissioning report [4].

11.2.2 Korean Research Reactors KRR-1 and KRR-2

The two Korean research reactors, KRR-1 and KRR-2, were decommissioned following a combined decommissioning plan. The two reactors were located in adjacent buildings at the KAERI's Seoul site. They were TRIGA Pool type reactors. KRR-1 was a TRIGA Mark-II with a fixed core, which could operate at a level of up to 250 kW, and KRR-2 was a TRIGA Mark III with a movable core, which could operate at a level of up to 2000 kW. KRR-1 started operation in 1962 and KRR-2 started operation in 1972; both were taken out of service in 1995 and replaced by a new and more powerful research reactor, HANARO, at the Daejeon site [5].

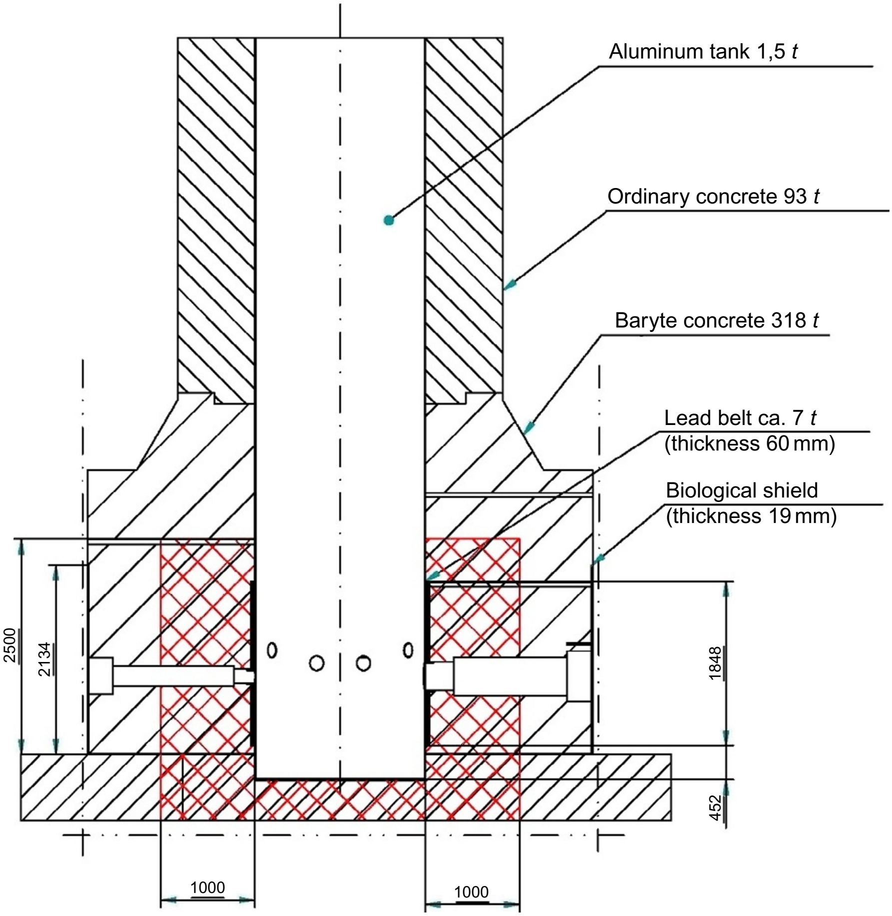

Fig. 11.3 Cross-section of DR2's biological shield. Only the crosshatched part had to be disposed of as radioactive waste.
From N. Strufe, 2009. Decommissioning of DR2. Final report. DD-38 Rev.1 (ENG). Danish Decommissioning, Roskilde. Available as a PDF-file from the Internet address: http://www.dekom.dk/media/24133/dr%20dr2_%20final%20report_eng.pdf.

The decommissioning project started in Jan. 1997 with characterization and licensing work and removal of the spent fuel to the United States. Dismantling of the reactors was carried out sequentially, starting with KRR-2 in 2001 and finishing with KRR-1, where dismantling works were completed by 2013. However, some radioactive waste still remains at the site and some remediation work on site and building is still pending as of Apr. 2016 [6] (Figs. 11.4 and 11.5).

The core structure of KRR-2 and other highly active internal components were cut into small pieces by hydraulic scissors and packed into a shielded waste cask underwater in the pool. Prior to cutting the shielding concrete, all facilities embedded in the concrete, such as the thermal column and beam port tubes, were dismantled. The graphite blocks, located in the thermal column near the core, were highly activated,

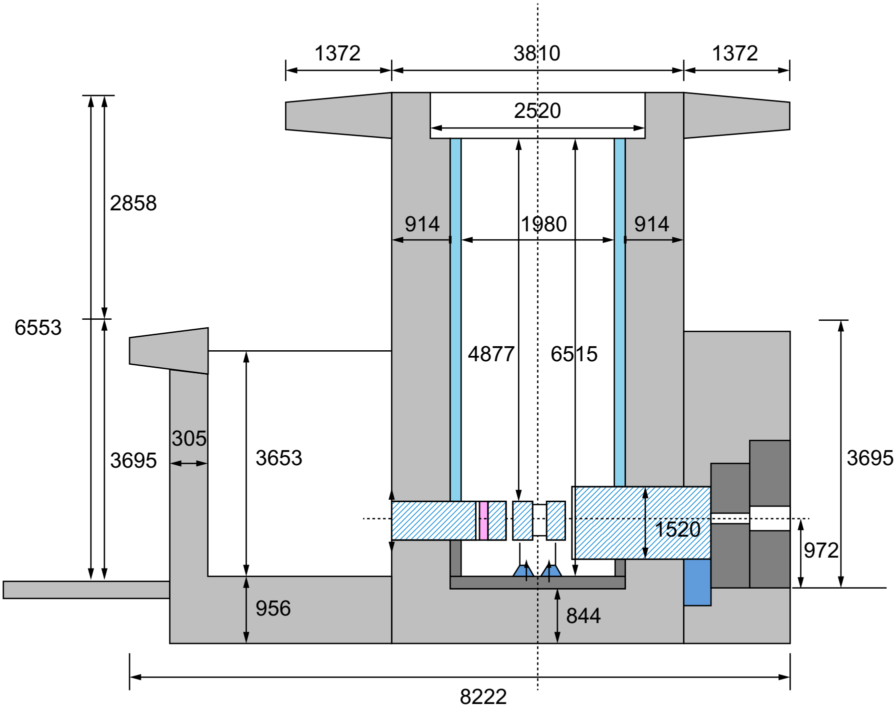

Fig. 11.4 Side view of the TRIGA Mark-II type reactor. Courtesy of S.-K. Park.

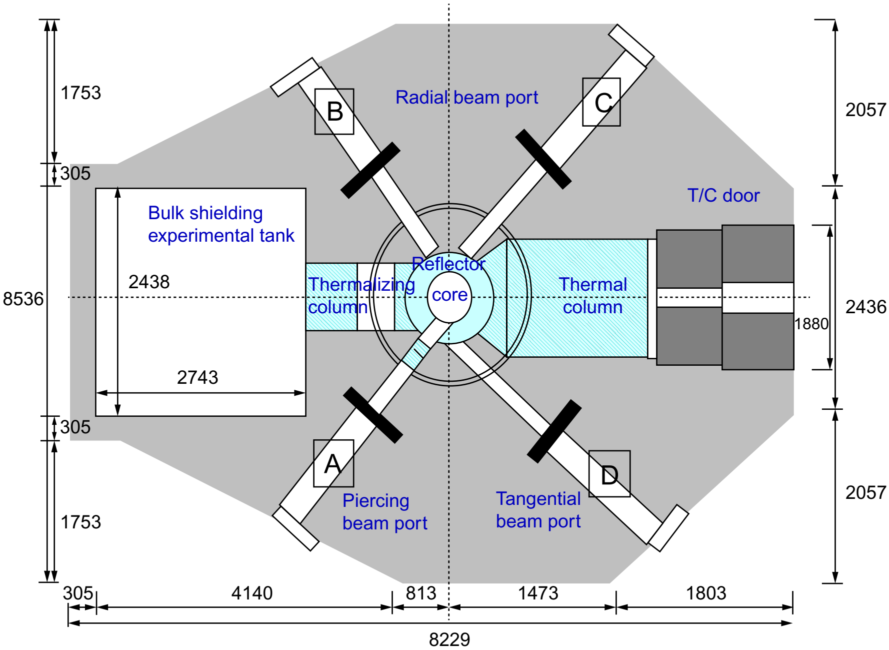

Fig. 11.5 Top view of the TRIGA Mark-II type reactor. Courtesy of S.-K. Park.

Fig. 11.6 Core drilling.
Courtesy of S.-K. Park.

and a specially designed and remotely operated gripping tool was used for pulling them out. The aluminum casing for the graphite was cut using a long-reach plasma arc. A core drilling machine with a 400-mm diameter diamond drill bit was used to remove the beam port pipes and the concrete around the pipes simultaneously, as shown in Fig. 11.6 [7].

The part of the biological shield that could be considered nonradioactive waste was cut down by means of wire cutting. Thereafter, a tent composed of plastic sheets was installed to cover all the activated parts and a breaker was utilized to cut the remaining concrete into pieces small enough to be packed into 4 m^3 waste containers.

Minimization of solid waste was an important issue in the strategy for decommissioning of KRR-1 and KRR-2 and was realized by repeated decontamination in order to free release as much as possible, adhering to the clearance criteria set by the Korean regulatory authorities.

It had been decided to keep the KRR-1 as a historical monument after completion of the decommissioning. However, due to the discovery of a leakage of water from the reactor pool, the plans were reviewed; it was decided to remove all radioactive material, including major parts of the biological shielding, before the building and the remaining concrete structure of the reactor could be released for unconditional access. At the moment (Apr. 2016) a governmental decision still awaits regarding which organization is to be responsible for the museum.

11.2.3 Japanese Reactor 2

The Japanese Reactor 2 (JRR-2) was a 10-MW tank-type heavy water reactor that was operating from 1960 until it was finally shut down in 1996 after fulfilling its purpose. In addition to the usual research reactor activities it also had a facility for boron neutron capture therapy (BNCT).

Dismantling activities began in Aug. 1997. As of 2014, JRR-2 was in safe storage, awaiting the start of operation of a low-level waste repository.

The decommissioning program was divided into four major phases with the following major tasks:

Phase 1

- Fuel elements were sent to the United States.
- Heavy water, about 16 m^3, in the reactor tank and the primary coolant system was drained to heavy water storage tanks.

Phase 2

- Disconnection of the reactor cooling system and sealing of the pipe ends at the reactor.
- Removal of experimental facilities and the BNCT facility.
- Sealing of all openings in the reactor body by welding plates onto them.
- Radiation monitoring tubes set up to monitor dose rate inside the reactor core during safe storage.
- Transportation of heavy water to Canada.

Phase 3

- Dismantling of the reactor cooling system
- Decontamination of the heavy water components using a heating decontamination device, consisting of a blower, a tritium trap, and a hot air dryer. This device operated with batches of max. 400 kg. The components were dried by hot air at 300–400°C for 2 h. The contamination (maximum 750 Bq/g) of the main heavy water heat exchanger tubes was reduced to maximum 2.5 Bq/g by this method.

Phase 4

- The reactor was placed in safe storage in 2004; cf. Fig. 11.7. Dose rates in the reactor have been measured once a year since then.
- When the low-level waste disposal facility is in operation the reactor body and, ultimately, the building will be demolished [8].

Fig. 11.7 JRR-2 in safe storage.
From M. Tachibana, et al., 2014. Experiences on research reactors decommissioning in the NSRI of the JAEA. Int Nuclear Safety J 3(4), 16–24. Available from the Internet address: http://nuclearsafety.info/international-nuclear-safety-journal/index.php/INSJ/issue/view/9.

11.2.4 The IFIN-HH WWR-S

The WWR-S was a 2-MW tank-type reactor using light water as coolant, moderator, and reflector. It was situated at the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) in Magurele near Bucharest, Romania. The reactor type is of Soviet origin and a number of similar reactors exist in the former Soviet Union and formerly associated countries. The reactor was in operation from 1957 to 1997, and the decision to decommission it was made by the Romanian government in 2002.

The decommissioning project started in 2010 and was carried out in three phases.

Phase 1 comprised the following activities:

- Removal of materials, equipment, and nonnuclear structures that did not affect the conduct of the following phases of decommissioning.
- Renovation of some systems preparing for the actual decommissioning activities.
- Preparing the reactor building for the work activities during the following decommissioning phases.

Phase 2 comprised the following:

- Decontamination.
- Start of dismantling and demolition activities.
- Radioactive waste treatment, conditioning, and removal in order to obtain a progressive reduction of contaminated areas.

Phase 3 comprises the following:

- Removal of all remaining reactor materials, equipment, and components, including most support utility systems, in order to be able to utilize the building without any restrictions after decommissioning.

Prior to the start of decommissioning work the spent HEU fuel elements were repatriated to the Russian Federation in Jul. 2009 by air transport, the first time in the world this method was used for this kind of nuclear material. The remaining LEU fuel elements were shipped back to Russia in 2012.

Dismantling of the reactor core and segmentation of the regulation rod represented special challenges because both were too active to be handled directly. The reactor core vessel was a cylindrical aluminum vessel with a diameter of 645 mm and a height of 800 mm. The dose rate at the surface was around 10 mSv/h. The vessel was lifted out of the reactor and placed on a turntable in a shielded cell built up from concrete blocks in the reactor hall. The core was segmented by means of a plasma cutter that was maneuvered through a narrow penetration in the shielding and surveyed by video cameras as shown in Fig. 11.8.

The boron steel regulation rod was the most active component from the reactor, giving a dose rate of 3 Sv/h at a distance of 50 cm. It was cut in smaller pieces directly into a shielded drum by means of shears mounted on a remotely controlled Brokk 160, as shown in Fig. 11.9.

Dismantling of the reactor internals resulted in the generation of 14.724 kg of metallic waste (steel, aluminum, and copper), of which 14.542 could be released as clean. 174 kg of aluminum and 8 kg of steel had to be disposed of as radioactive.

All decommissioning activities at the reactor are scheduled to be completed in 2018 and the radioactive waste will be transferred to a newly refurbished waste-handling facility at the site. The buildings are planned to be reused for a new Extreme Light Infrastructure for Nuclear Physics (ELI-NP).

Fig. 11.8 Plasma cutting of reactor core in a shielded cell.
Courtesy of C. Dragolici.

Fig. 11.9 Cutting the automatic regulation rod.
Courtesy of C. Dragolici.

11.2.5 NASA's Plum Brook Reactor

The final dismantling of the Plum Brook reactor internals illustrates the fact that deferred dismantling may be complicated [9]. The reactor was a 60 MWt PWR that operated from 1962 until 1973, when the water was drained and the facility mothballed. Final dismantling of the reactor vessel internals commenced in 2003.

Without water in the vessel to provide shielding the radiation levels at the top of the vessel were so high that even leaning over briefly to look into the vessel was out of the question. Therefore, it was not possible to use tools operated with conventional long poles from above with direct visual control. Instead a heavy shielded "hat" with a wall thickness of about 230 mm was placed over the reactor vessel, and via a hole in the top of this "hat" tools at the end of long poles could be positioned vertically by means of an electrical hoist. Horizontal gripper poles were then used to manipulate the tools in the horizontal plane aided by cameras placed inside the vessel. Mock-up training was used by the operators to learn this special type of working with long poles.

Even after 30 years of decay the control rods exhibited exposure rates of over 10 Gy/h at contact and, therefore, needed to be sectioned remotely by means of a hydraulic shear while still inside the reactor vessel. The most active sections were transported from the reactor vessel to a shielded liner during lunch break with all personnel onsite removed from the area. During this operation site personnel could not exit through the portal monitors due to the increased background levels. The crane operator and radiation protection personnel were the only ones in the immediate area.

For this project with particularly high activity levels mock-up practicing was valuable, saving time and exposure and helping devise optimal ways of carrying out the work. During a mock-up test personnel were encouraged to stop and ask questions; and they did. Sometimes this delayed the start of work, but the work was accomplished successfully because everyone was ready and understood their scope [9].

The dismantling of the Plum Brook reactor was completed in 2010, and in 2012 the building was demolished and the area remediated [10].

11.3 Planned decommissioning projects

According to the requirements and guides from the IAEA, decommissioning planning should start already from the design of a nuclear facility or as soon as possible. Since most of the world's research reactors were designed long before this requirement was formulated, few of them had a decommissioning plan in the early 2000s. However, the regulators in many IAEA member states have now implemented the requirement on a national basis, and many decommissioning plans are now being produced, both for reactors close to decommissioning and for reactors foreseen to continue operation for a long time into future. A number of examples will be given below, based on available literature. However, detailed decommissioning plans are not very common in the published literature because they are considered proprietary or limited for distribution to regulators.

11.3.1 Finnish Reactor 1 (FiR-1)

The FiR-1 at the Technical Research Centre of Finland (VTT) operated from 1962 to 2015 and was the only research reactor in Finland. It was a 250 kW TRIGA Mk II reactor, and in addition to the neutron physics applications typical for research reactors it served as a training facility for personnel for the two Finnish nuclear power plants. Swedish nuclear professionals also received training at the reactor. Furthermore it had a BNCT facility that was operating from the 1990s until 2012. In 2012 VTT decided to shut down FiR-1 as soon as technically and legally justified. VTT considered the reactor as “a profit unit without a strategic role for VTT,” and the income from the reactor services no longer covered all the costs of the reactor, especially after the closure of the BNCT facility.

During 2012–13 a number of meetings were held between VTT, the regulatory authority, STUK, and the Ministry of Employment and the Economy, to which VTT belongs, in order to agree on the process of planning and implementation of decommissioning. In early 2013 the preparation of an environmental impact assessment (EIA) was initiated as one of the first steps in decommissioning planning. The EIA was produced for VTT by a consultant, Pöyry Finland Oy, with expert input from VTT staff concerning radiological issues. It was completed in Oct. 2014 and published in Finnish and Swedish on the home page of the Ministry of Employment and the Economy website after the ministry’s approval [11]. The document is a 189-page report that also addresses a number of issues that often are included in a decommissioning plan, such as an overall description of the dismantling works, radiation protection during decommissioning, and waste-handling issues.

Due to the foreseen workload from decommissioning activities and a limited number of VTT staff, it is planned to engage partners or subcontractors for most of the work. Several similar reactors have been decommissioned: for instance Heidelberg 2 (HD-2) and Frankfurt 1 and 2 (FRF 1&2) in Germany, DR2 in Denmark, and KRR-1 in Korea. Experience from those projects will be drawn upon. Furthermore, the FiR-1 decommissioning could be seen as a pioneering project for domestic nuclear power utilities that will face decommissioning later on, thus making it attractive for the power utilities to take a part in the work. The decommissioning of FiR-1 will be carried out under an amended operating license because the concept of a “decommissioning license” does not exist in the Finnish legislation.

The decommissioning planning currently (2016) focuses on three issues: spent fuel management, procurement of dismantling planning and execution, and preparations for interim storage of the dismantling waste. The fuel is subject to the return program of the US Department of Energy (DOE), which runs until May 2019. The primary scenario for disposal of the nuclear fuel, therefore, is to send it back to the United States. A secondary option would be final disposal in Finland, possibly in conjunction with fuel from the Finnish power plants. However this would require relicensing of the encapsulation and spent fuel disposal facilities to be constructed in Olkiluoto on the western coast of Finland. The dismantling will yield a small volume and inventory of low- and intermediate-level waste, some tens of cubic meters. Final disposal of this waste is intended to be in the waste repositories of the Olkiluoto or Loviisa NPPs. An interim storage period of about 20 years is foreseen and VTT is investigating alternative locations for storage.

According to the preliminary schedule shown in the EIA, dismantling work will start by mid-2016 and finish by the end of 2018, so that the building could be released for other purposes in 2019.

The following references provide further information about FiR-1 and the decommissioning planning: Refs. [12–14].

11.3.2 Greek Research Reactor 1

The Greek Research Reactor (GRR-1) is a 5 MW open pool type, light water reactor designed by AMF Atomics. The reactor is located on the campus of the National Centre for Scientific Research, "Demokritos" (NCSRD) in the Aghia Paraskevi district of Athens. Its main experimental facilities are six beam tubes, a thermal column, a dry irradiation chamber, a pneumatic conveyor, vertical tubes and suitable baskets for irradiations, and rotating systems for uniform multiple irradiations.

In 2007, a decision was made to refurbish and modernize the reactor, including a replacement of the primary cooling system. The reactor has been in extended shut down since Jul. 2014, and at present (May 2016) it is unclear whether the refurbishment plans will be carried through or the reactor will be fully decommissioned. Due to the country's financial situation the refurbishment and modernization of the GRR-1 was stopped abruptly. At the moment there is no political decision about the future of the reactor, which remains in extended shutdown.

However, during the period of extended shutdown a partial decommissioning plan for dismantling of the primary cooling system was submitted and approved, and partial dismantling of the reactor systems carried out in accordance with the primary cooling system refurbishment project [15].

A predismantling radiological characterization of the primary cooling system by using in-situ gamma spectrometry was carried out, as well as neutron calculations for the grid plate, control rods, and beryllium blocks. Five out of six beam tubes, the control rods, the beryllium reflector blocks, and the active core supporting components (grid plate, plenum, etc.) were removed from the reactor pool and transferred to the spent fuel storage pool and other shielded storage structures. Then the reactor pool and the pool cooling system were drained and a radiological characterization of the pool cooling system was accomplished by collection and analysis of representative samples from the internal surfaces of the systems. The classification of the waste that will arise from the decommissioning of GRR-1 is based on considerations of long-term safety of waste disposal (IAEA Safety Standards Series GSG-1, Classification of radioactive waste).

The decommissioning strategy is removal of all activated and contaminated parts without demolition of the biological shielding. The spent fuel will be sent to the United States, according to the agreement with the DOE for shipment until 2019. The reactor building will be reused in the nuclear sector. Clearance procedures will be followed for release of building structures and materials.

In Refs. [16], [17] and [18] characterization of the reactor components and systems with a view to decommissioning planning is described in detail.

11.3.3 BEPO

The BEPO (British Experimental Pile Zero) at Harwell is one of many legacy facilities in the United Kingdom that are awaiting their final decommissioning. The 6 MW reactor was commissioned in 1948 and used primarily for the production of radioisotopes, general irradiations, chemical engineering experiments, and as a source of neutrons for nuclear measurements. The reactor had a graphite moderator and was fueled by natural or low enriched uranium and cooled by air. It operated until 1968 and defueling was completed the following year.

A program involving the removal of the chimney and restoration of the land surrounding BEPO was completed in 2000.

Characterization of the reactor graphite core was carried out in 2014 [19]. The work involved surveying around 60 of the horizontal fuel channels using a probe fitted with a gamma sensor and a camera. The probe is deployed some 10 m into the reactor using a continuous reel of a reinforced plastic that springs into a stiff rod shape. The survey information will be used to plan the decommissioning of the reactor.

While BEPO was in operation, a large concrete block containing 250 tubes was used to store fuel elements and rigs from BEPO. Around 175 of these tubes are over 8-m long and only 3.5 cm in diameter. These storage tubes were opened in Mar. 2013 for the first time since 1969, and the levels of residual radioactivity in the tubes were found to be higher than previously anticipated. Because the concrete block surrounding the storage tubes is to be demolished it was found necessary to fix the radioactivity due to the risk of fracturing the tubes during the demolition. However, traditional methods to fix contamination were not considered appropriate due to the size, shape, and positioning of the tubes. Instead, expanding PU foam was used with success. The work was completed in Mar. 2014 [20].

The BEPO reactor will remain in care and maintenance until around 2040, when the core and remaining facilities will be completely decommissioned.

11.3.4 CONSORT

The UK nuclear regulator, the Office for Nuclear Regulation (ONR), in Aug. 2015 approved the application to decommission the CONSORT research reactor at Imperial College London's Silwood Park Campus in Berkshire [21].

The 100 kW reactor began operations in 1965 and was shut down in 2012 due to increasing costs and a lack of research, educational, training, and commercial use. The reactor's fuel was removed and transported to Sellafield for storage in Jul. 2014.

The decommissioning project will involve the removal of all radiological and non-radiological material to enable the site to be delicensed. The ONR attached conditions to the approval that the Imperial College "ensures mitigation measures are implemented to minimise the environmental impact of the project." This includes requiring Imperial College to prepare an annual environmental management plan updating on the project's progress and reporting on the effectiveness of the mitigation measures. The college must also notify the ONR in advance of any significant change to a mitigation measure.

The college anticipates all of the reactor's physical structures being removed from the site by late 2019 and final site delicensing in 2021. The site will then be "suitable for any purpose the college considers best supports its academic mission [21]."

11.3.5 Kiev WWR-M

The WWR-M is a light water cooled and moderated heterogonous research reactor with a thermal output of 10 MW and a maximum neutron flux of $1.5\times10^{14}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the core center. It was designed and constructed in 1957–60, and the first criticality was achieved in Feb. 1960. It is located on the site of the Institute for Nuclear Research (INR) in the Goloseev district of Kiev city. The reactor is currently in operation and its operational license runs until the end of 2023 [22].

An initial decommissioning plan was completed in 2009, and work with the final decommissioning planning is in progress now. The decommissioning planning foresees the strategy of immediate dismantling with reference to plans for further site use. The ultimate goal of the reactor decommissioning is unrestricted site use with transfer of the reactor building, part of the existing infrastructure, and the auxiliary building to a separate laboratory for the development and application of radiation technologies.

The general dismantling strategy comprises the following main issues:

- dismantling will be performed "from top to bottom" for the preservation of stability
- dismantling and removal of the separate bulky elements as whole pieces, without preliminary segmentation
- subsequent segmentation of such elements, if necessary.

The dismantling is planned to be carried out in three main stages. The first stage includes dismantling of the equipment around and inside the reactor and in the biological shielding. The second stage includes dismantling of the primary cooling circuit. Demolition of the biological shield will be carried out as the third stage.

The dismantling of the primary cooling circuit is considered one of the key tasks and a separate dismantling plan has been developed for this part. Ref. [23] gives a detailed description of the cooling circuit and the dismantling plan (Figs. 11.10 and 11.11).

Major tasks in the dismantling of the primary cooling circuit will be removal of the heat exchangers, dismantling of piping, and dismantling of ion exchange and electrophoresis filters. Dismantling and removal of larger components, in particular the heat exchangers, will be challenging due to the limited space available. But it is expected that they can be taken out as whole pieces and brought to the segmentation area or an intermediate storage facility.

The segmentation will take place in the reactor hall (after removal of the reactor internals, etc.) where a special area will be prepared for the purpose, and where the existing bridge crane will be available for heavy lifts.

In Ref. [23] it is mentioned that the decommissioning planning has been drawing upon the experience from other similar facilities (e.g., in Bulgaria, Greece, Austria, and Denmark). Likewise, in the article [24] the decommissioning plan for the Kiev

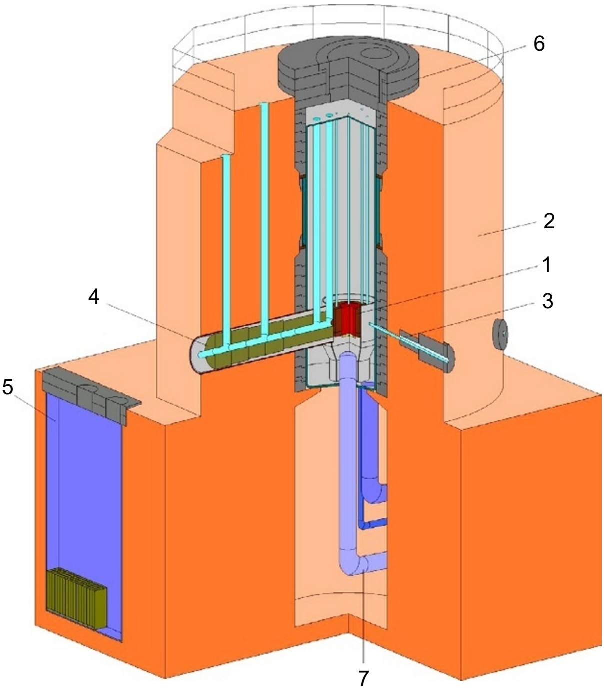

Fig.11.10 Sketch of the WWR-M.
Courtesy of Y. Lobach.

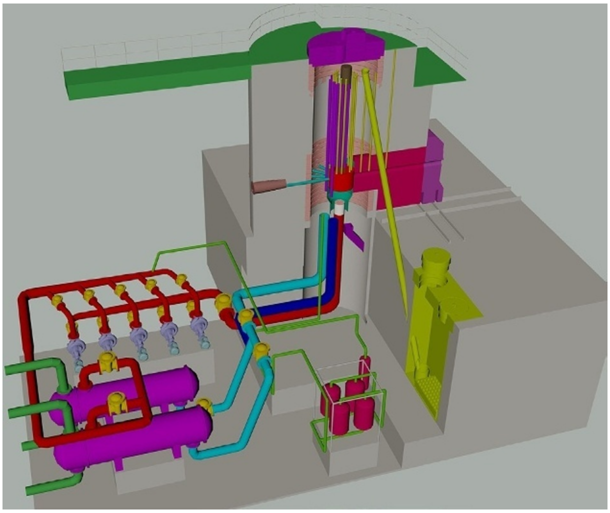

Fig. 11.11 Sketch of the cooling system.
Courtesy of Y. Lobach.

WWR-M is extended to a proposed "general decommissioning plan" for WWR research reactors. There are nine WWRs that are still operational, but they will soon face decommissioning. The reactors have similar basic designs, so that it makes sense to utilize experience from one to another.

11.4 Common issues of research reactor decommissioning

In this section a number of common factors, challenges, and options for research reactor decommissioning will be discussed. They have all played a part in the decommissioning projects described in the previous sections but have not been discussed in detail there.

11.4.1 Aimed or achieved end states

The guidelines from the IAEA recommend release from regulatory control without restrictions (greenfield) as the preferred end state and ultimate objective of decommissioning [25]. However, it is recognized that this may not be possible or desirable in all cases, for example, if part of the facility is going to be reused for other purposes involving radioactive material or if the cost of decontamination of the facility to below clearance levels is excessive. In such cases the end state will be release from regulatory control with restrictions, often referred to as brownfield. A decommissioning strategy involving entombment of the facility is in general not considered acceptable, but there are examples where this has been seen as the best-or only-solution; cf. Section 11.4.1.3 below.

11.4.1.1 Greenfield

In cases where no future nuclear activities at the site are foreseen release from regulatory control without restrictions will be the natural end state for a decommissioning project. This is the case for the Risø site in Denmark, where all decommissioning projects are planned to be completed by 2023. However, political failure to agree on a site for a waste repository may extend the period with radioactive material in interim storage at Risø for several decades. The Korean reactors, KRR-1 and KRR-2, mentioned in Section 11.2.2, have been decommissioned to a greenfield status even though there are other nuclear activities at the site. The same is the case for the Japanese JRR-2, mentioned in Section 11.2.3, and the Plum Brook reactor (Section 11.2.5).

For the planned decommissioning projects mentioned earlier in this chapter the FiR-1 (Section 11.3.1) and the CONSORT reactor (Section 11.3.4) will be decommissioned to greenfield within a short timeframe. The BEPO (Section 11.3.3) still faces another 40 years before final decommissioning will take place, probably to greenfield.

11.4.1.2 Brownfield

In cases where future nuclear activities at the site are foreseen, maybe using part of the old facility, it may not make sense to decommission down to below release criteria. This can be the case for the GRR-1 (Section 11.3.2) if it is decided to renovate the reactor and for the WWR-S at IFIN-HH (Section 11.2.4), where it is planned to establish an electron accelerator in the building.

A number of legacy facilities from the early period of the nuclear age have been or will be decommissioned with brownfield as the end state, either because they are located at a still functioning site or because total cleanup will be very expensive. One example of such a facility is the Graphite Research Reactor at Brookhaven National Laboratory. The reactor building will remain and an engineered asphalt cap system has been built around this building to prevent rainwater from mobilizing any residual contamination in subsurface soil and remaining concrete structures in the ground beneath the building. Additionally, an extensive groundwater monitoring system has been installed [26].

11.4.1.3 Entombment

In 2014 the editor of the present book wrote an article concluding the following:

> *Regardless of negative national and international positions, entombment remains a viable decommissioning strategy in several cases for example:*

- To achieve a safer configuration of a shutdown reactor in a country or institution lacking basic infrastructure (e.g., dismantling expertise or funds, waste disposal prospects, etc.).
- When adequate surveillance of the entombed facility can be ensured, typically when the facility is situated in a wider site bound to remain operational or under institutional control for a long time.
- The use of entombment is limited to a small number in a given country, particularly to remote sites, in order to prevent the uncontrolled proliferation of waste disposal sites.
- To leave open the option of dismantling entombed structures in a not-too-distant future [27].

The article gives a number of examples of entombment projects that have been carried out or are being planned. It is not the intention here to repeat these examples and the argumentation for the acceptability of entombment in individual cases. But it is a fact that the strategy is being applied, in particular in the United States and Russia, where a number of facilities from the early years of the nuclear age represent special challenges as far as decommissioning is concerned.

Although the IAEA does not recommend entombment as a strategy for planned decommissioning projects, the fact that entombment has to be used in some cases has led the agency to work on ways to establish recommendations on the subject [28].

11.4.1.4 Renovation of the reactor or reuse of part of the facility

Renovation of a reactor is not really an end state of decommissioning of the facility, but there are some projects that can be seen as the decommissioning of the old reactor, leaving most of the structure and equipment for a new reactor or other activities. One example is the IRT-2000 research reactor in Sofia, Bulgaria. This 2 MW reactor was operating from 1961 to 1989. In 2001 it was decided to reconstruct the IRT-2000 into a reactor of low power up to 200 kW. All highly (HEU) and low enriched (LEU) Russian-origin nuclear fuel was repatriated to Russia in 2003 and 2008 in the frame of the Russian Research Reactor Fuel Return Program (RRRFR). The dismantling of obsolete reactor systems was successfully completed in 2009, preserving the biological shielding. The establishment of the new reactor will include installation of new control systems for radiation surveillance and physical protection, in addition to the reactor control system itself. Also laboratory facilities will be renovated or newly built. The partial dismantling and the new reactor system are well described in a number of publications, for example, Refs. [29] and [30]. At the moment (spring 2016), however, the EIA has been challenged by the "green" parties and the court has approved the challenge, so that a new EIA will be required in order to relaunch the IRT-200 project. The funding for the project has been suspended by the government, and the fear is that the government will decide on the full decommissioning of the reactor and no construction of a new one.

11.4.2 Experience related to decommissioning planning

11.4.2.1 Factors leading to the decision on decommissioning

As many of the world's research reactors are around 50 years old or more a common reason for the decision to decommission a reactor is that it has reached the end of its useful life. However, there are a number of examples where economy, accidents, deterioration of the equipment or political interference has played the decisive role. The latter factor has been involved for several of the decommissioning projects mentioned in this chapter and has often been fostered by hostility towards nuclear technology in general. One slightly positive note in this context could be that funding for publicly owned facilities—might flow easier if there is a strong political desire to get rid of the reactor. Another factor that has played a role for a number of research reactors is the possible expiration date for an agreement with the United States or Russia regarding the return of spent fuel; cf. Section 11.4.3.1.

11.4.2.2 Decommissioning strategy

The selection of the decommissioning strategy depends on a number of factors, such as the following:

- Safety aspects;
- Physical and radiological status of the facility;
- Interdependencies with other facilities or infrastructure located at the same site;
- Proposed reuse and desired end state;
- Availability of expertise, technologies, and infrastructure;
- Availability of infrastructure for radioactive waste management, including disposal options;
- Availability of financial resources for decommissioning.

In cases where there are concrete plans for reuse of the building or site immediate dismantling is the obvious choice, as has been the case for a number of the facilities mentioned previously. Another obvious argument for immediate dismantling has been the availability of knowledgeable staff from the operational period.

Even though immediate dismantling is the preferred strategy recommended by the IAEA there are also many examples where deferred dismantling has been selected. For the DR2, mentioned in Section 11.2.1, it was decided when the reactor was shut down in 1975 to defer dismantling until all facilities at the site were to be decommissioned. When this became relevant immediate dismantling was chosen as the strategy in the sense that decommissioning of the first facility started immediately and the others followed in sequence with the aim to finish decommissioning of the site within 20 years.

In countries with a large number of legacy facilities there is a need to prioritize the decommissioning of individual facilities, especially taking into consideration the economy and the physical and radiological status of the facilities. Therefore, decommissioning of facilities in good condition and with a low risk potential can be deferred for decades such as, for instance, BEPO (Section 11.3.3), PLUTO, and DIDO at Harwell in the United Kingdom.

The existence of a repository for radioactive waste is considered a prerequisite for initiating a decommissioning project. In many cases, however, decommissioning has started when there were only plans or intentions to establish a repository, and in some cases the repository has materialized in time. In other cases, such as the Danish one, even a unanimous vote by Parliament in 2003 to establish a national repository has not led to anything close to a result in 2016.

11.4.2.3 Cost assessment and financing

Cost assessments have been implemented in different ways for different facilities, and they often have not been published. But since 1999 a number of organizations have used the "Yellow Book" [31] and its successor, the ISDC [32], as a source of inspiration and checklist in order to remember all important issues that have to be taken into account when estimating the cost of a decommissioning project. Other organizations have used traditional project cost estimation methods, in some cases supported by specialist consultants. For the Danish facilities a mixture of these approaches was used [3]. Future decommissioning projects for research reactors may use the tool CERREX, discussed in Section 11.4.4.4 [48].

As far as financing is concerned many research reactors, including all of those mentioned in this chapter, are state-owned or owned by public organizations. Therefore, the bill ends with the state budget (and the taxpayer). In some cases this has come as an unwelcome surprise to governments and parliaments, since funding has rarely—if ever—been set aside during operation. On the other hand most state budgets have been able to absorb the cost, with or without the support from external sources; cf. Section 11.4.4.3 about the IAEA's assistance to certain decommissioning projects.

11.4.2.4 Learning from others

In addition to the exchange of experience between decommissioning projects in the framework of IAEA programs, mentioned in Section 11.4.4, there are examples of more or less formal groups of owners of similar type of facilities who exchange information, such as the “DIDO group” for reactors similar to the DIDO reactor at Harwell. Staff from the six DIDO-type reactors in the United Kingdom, Australia, Germany, and Denmark met on a regular basis during the operational period to exchange experience, and the contact continued in particular when the non-UK reactors started decommissioning planning more or less at the same time. At the moment the two reactors at Harwell (PLUTO and DIDO) are in safe enclosure for a number of years to come, while the other four reactors (DMTR in Dounreay, HIFAR at Lucas Heights, FRJ-1 in Jülich, and DR3 at Risø) are under decommissioning with a goal of completion within a few years.

In Germany there is a group called *Arbeitskreis Stilllegung der Arbeitsgruppe Forschungsreaktoren* (~Decommissioning Subgroup of the Research Reactor Work Group), which included staff from a number of reactors in the German-speaking countries of Germany, Austria, and Switzerland, in addition to Denmark, where the German language is understood. The group typically held meetings twice a year.

Similar cooperation has taken place between owners of WWR-type reactors and Triga reactors.

11.4.2.5 “Do it yourself” or contracting

Especially in cases where decommissioning is performed immediately after final shutdown the operational staff may carry out the dismantling, or part of it, by themselves, whereas there will be a need for external assistance if the reactor has been shut down for many years and no or few staff members knowledgeable of the facility remain at the site. For all of the reactors mentioned in Section 11.2 the operational staff has been involved in the dismantling, possibly with the addition of new personnel with competences that were not available during operation. In the Danish case a contractor was performing the demolition work, and a number of new staff members were hired with competences in, for instance, management of large projects.

For facilities that have been shut down for a long time or where the remaining organization is small, dismantling has to be undertaken by new staff and possibly managed completely by contractors; this will be the case for BEPO and FiR-1.

11.4.3 Aspects related to decommissioning

11.4.3.1 Fuel repatriation

A large number of research reactors have initially used highly enriched uranium fuel (HEU) in order to have the best performance possible with respect to their applications in physics research and isotope production. However, when India performed its first test of an atomic bomb in 1974 global concern was raised about the export of fissile materials and technologies [33]. Over the following years a number of initiatives were taken to reduce the use of HEU and to control the whereabouts of fissile material. In particular the United States and the Soviet Union launched programs in this respect, and the IAEA was given the task to secure full-scope safeguards for transfers of nuclear materials and technologies. The IAEA, furthermore, established guidelines for the physical protection of civilian sites and materials and established programs to assist Member States with the development and qualification of new research reactor fuels, as well as striving to minimize civilian use of highly enriched uranium (HEU) by converting HEU fuels to low enriched uranium (LEU) and assisting states in dealing with spent nuclear fuel [34].

Ref. [33] gives a good overview of all the initiatives in this respect, some of which give the owners of research reactors the possibility to return spent (and fresh) fuel to either the United States or Russia. These programs include the Reduced Enrichment for Research and Test Reactors (RERTR), the US Foreign Research Reactor Spent Nuclear Fuel (FRR SNF) Acceptance Program, and the Russian Research Reactor Fuel Return (RRRFR) Program. In addition to reducing the threat of the proliferation of bomb-grade material these programs remove the need to establish repositories for long-lived material in many countries that have only research reactors.

11.4.3.2 Remote vs. manual or semimanual dismantling

Some dismantling tasks will have to be carried out by means of remote operated tools or machines due to very high radiation levels. The only alternative would be to choose deferred dismantling as the decommissioning strategy with a deferral period of several decades, and this in reality would only be practicable at multifacility sites and not for one individual research reactor. For research reactors the candidates for remote handling most often are found in the core region where the highest activation has taken place. The degree of remote handling may include the use of advanced remote controlled machines, but they are more often ad hoc solutions with temporary shielding and long-reach tools, such as those described for the DR2 (Section 11.2.1), the IFIN-HH WWR-S (Section 11.2.4), and—slightly more sophisticated—the Plum Brook Reactor (Section 11.2.5). Another option, still remote controlled, is segmentation underwater as for the KRR-2 (Section 11.2.2).

Obviously, remote handling will reduce the radiation dose for personnel; on the other hand it is in general more time consuming than hands-on operations and may result in more equipment to be decontaminated later or disposed of as radioactive waste.

In the borderline cases the choice of whether to apply remote or manual dismantling often will be a balancing between economy and dose reduction, taking into consideration also the preferences of the staff and the general approach to dose minimization at the facility and by the regulator.

11.4.3.3 Waste segregation and minimization

The waste resulting from a decommissioning project is a mixture of radioactive material and nonradioactive material, some of which may be recycled while another, generally smaller, part contains toxic or otherwise dangerous chemicals.

Because the cost of disposing radioactive waste in a repository is high there is an incentive to reduce the amount as much as possible, and this involves considerations to be made during planning of dismantling as well as sorting of material after dismantling. Model calculations and characterization measurements prior to the planning phase will serve to give a (rough) picture of the distribution of active and nonactive material so that the segmentation of components and the demolition of biological shields can be carried out in an optimal way with a view to minimizing the radioactive fraction. Once the waste has been produced the volume may in some cases be reduced further by incineration of burnable waste and melting of metallic waste so that the radioactive elements will be concentrated in the ashes and slag, respectively. A number of companies offer these services, but in some cases the expenses and difficulties involved with the transport of the waste may outweigh the costs of direct disposal.

In countries that allow the free release and recycling of material with radioactivity content below fixed clearance levels there will be a further need to segregate the material in fractions according to national regulations: for example, metals, burnable material, and chemically toxic materials.

11.4.3.4 Clearance criteria

Many countries in their legislation permit free release of material from nuclear facilities if the activity content falls below prescribed limits, the clearance limits. Other countries do not permit free release, but they may instead have a waste category, very low-level waste (VLLW) that can be disposed of in less sophisticated repositories than those built for higher level wastes.

National clearance levels for the clearance of solid materials are often based on the recommended values set out by the IAEA in Refs. [35] and [36], where mass specific clearance levels are given for a large range of nuclides. With a view to the clearance of buildings for reuse the European Commission has issued recommended values for surface specific clearance levels [37].

11.4.3.5 Heavy water and tritium

For heavy water reactors the heavy water itself may pose a costly waste problem, unless the organization or country has other facilities that can utilize the heavy water. If the water is to be exported this will involve expenses for removal of tritium and other impurities as well as for upgrading the heavy water: in other words, removal of light water. Furthermore, the transportation itself can be a costly affair.

Tritium is a low-energy beta emitter with a half-life of 12.3 years. It is produced predominantly by activation of deuterium in the heavy water and may move into deposits on the piping of the cooling systems or even into the metallic surfaces themselves, thus becoming an issue to be considered by possible clearance measurements or when disposing of the material as radioactive waste. In the latter case precautions must be taken to ensure that tritium does not leach out from the waste and creates elevated levels in the repository. This can be done by immobilization, and Ref. [38] discusses this subject in some detail. If the tritium levels are low but the material has to be considered radioactive waste for other reasons, melting may be an acceptable solution, in other words, if the resulting release of tritium to the atmosphere is within emission limits. If a heavy water reactor has had leakages from the primary system tritium may be found in the concrete of the biological shield, necessitating removal or immobilization.

If the material is considered for clearance it is necessary to document that the contents of tritium in the solid material is below clearance levels. As tritium emits only low-energy beta radiation this cannot be done just by surface measurements but has to be based on samples taken from the material that are dissolved and measured by, for example, scintillation counting. This is a lengthy and costly procedure because many samples are needed. Ref. [39] describes a Danish case where 15 samples were needed to provide a sufficiently low uncertainty.

11.4.4 The role of the IAEA

The International Atomic Energy Agency, IAEA, supports safe decommissioning of research reactors in a number of ways, both at the general level and by addressing individual decommissioning projects [40], [41], and [42].

11.4.4.1 Establishing requirements and guidelines

The numerous requirements and guides produced by the IAEA [43] play a particularly important role for organizations embarking on research reactor decommissioning because each organization most often only has one to three reactors to decommission. Particularly for in countries with one or a few research reactors and no nuclear power plants, the IAEA's system of safety guides provides very useful guidelines and even "recipes" for both regulators and operators.

Much of the development of safety guides during later years has been inspired by the outcome of two large projects, DeSa (DEmonstration of SAfety for decommissioning) and FaSa (Follow-up project on Application of Safety Assessment), both of which are dealt with in more detail in Chapter 2 of this book. DeSa project [44] was entitled "Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material" and was running from 2004 to 2007. FaSa was a follow-up project aiming at the practical use of safety assessment in planning and implementation of decommissioning. Some case studies in both DeSa and FaSa related to research reactors.

11.4.4.2 Supporting planning and execution via workshops, training courses, and projects

A number of initiatives from the IAEA, for example, in the form of regional workshops and training courses help in qualifying staff from organizations having upcoming decommissioning projects. These events, as well as, for instance, the International Decommissioning Network, IDN [45], also contribute to establishing networks for decommissioning staff from different organizations and countries.

One particular project has been the R^2D^2P (Research Reactor Decommissioning Demonstration Project) [46]. The approach of this project is to hold workshops that provide "hands-on" experience to participants. The focus of the project is on demonstrating the decommissioning of a research reactor. The scope includes all aspects of the decommissioning process, from establishing a legal and regulatory infrastructure to the final release of the facility from regulatory control. A total of 14 workshops have been held at facilities in different parts of the world that served as teaching laboratories for participants. The participants have received training through lectures and practical insights into the matters at the given site. The project commenced in Jun. 2006 and ended in 2015. Representatives for 14 countries have participated in the project. Documentation from the workshops is available on the IAEA website [47].

Furthermore, the IAEA organized two major conferences on the subject of decommissioning, one in Athens, Greece, Dec. 11–15, 2006, and one in Madrid, Spain, May 23–27, 2016.

11.4.4.3 Supporting specific decommissioning projects with equipment and consultancy

Especially for countries eligible for financial support from the IAEA the agency can ease the decommissioning planning and implementation by supporting the acquisition of important but costly equipment such as personnel contamination monitors. This happens via the IAEA Technical Cooperation Programme, TC. Likewise, dedicated consultancy can be given by international experts funded by the TC. Many decommissioning projects participating in the R^2D^2P and others mentioned earlier in this chapter have received such support.

11.4.4.4 Development of software tools

In a collaboration among the IAEA, the OECD/NEA, and the European Commission, the ISDC (International Structure for Decommissioning Costing of Nuclear Installations) was published in 2012 [32]. In addition to providing a useful checklist for decommissioning project planners the ambition was that the ISDC should ensure harmonization and comparability of D&D cost studies among projects: “apples with apples, oranges with oranges.” On the basis of this structure the IAEA supported the development of an Excel tool called CERREX (Cost Estimate for Research Reactors in Excel), directed specifically at research reactors [48]. The tool comes on a CD together with the book [48], which includes a number of examples. It is already being used at the planning stage for several research reactor decommissioning projects and is subject to comparative studies in the IAEA’s DACCORD project, which completed in 2015 with the final reporting still pending.

11.5 Conclusion

Decommissioning and decommissioning planning is ongoing for an increasing number of research reactors around the world. The reasons for decommissioning may include the reactor simply reaching the end of its technically useful life or-in a few cases—accidents that have left the facility in an irreversible condition, in addition to less rational political decisions. As the examples given in this chapter show, decommissioning can be carried out successfully and in most cases to an end state without restrictions.

Due to the variety of types of research reactors different challenges may be met at the individual facilities, but international cooperation and open exchange of information has helped the planning and conducting of decommissioning for many reactors, often supported by the IAEA.

The challenges met by decommissioning projects may be manifold. One of the first challenges often concerns financing, because funding has not been set aside during operation; but for those research reactors that are state-owned or otherwise publicly funded the financing has been made available, possibly following some political turmoil. On the technical side challenges may have their origin in the fact that most of the existing research reactors were designed without much attention to their future decommissioning; therefore, some dismantling tasks become difficult. Furthermore, due to the age of the reactors some important historical information may be lacking because staff from the early years is no longer available. Yet another challenge during decommissioning will be the fact that the time horizon is relatively short and the staff will know that the job comes to an end; the skilled people who are necessary for the planning and conducting of the work may, therefore, be tempted to leave prematurely, and new staff has to be hired and trained. Attempts to mitigate this situation could include contracts with a bonus for remaining in the organization until a certain point of time.

In the coming years more research reactor decommissioning projects will be initiated and new challenges may arise, but at the same time more experience will be accumulated to the benefit of future projects.

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Decommissioning in a multifacility site

12

M. Laraia
Independent consultant, Rome, Italy

12.1 Introduction

Multifacility sites include separate or connected facilities, independent or combined licenses, and common or distinct owners and organizations. Interactions between facilities include aspects such as the sharing of common systems, staff rotation, the synergies or competition between companies owning adjacent facilities, etc.

Multifacility sites are situated in many countries, and they house an ample range of nuclear facilities such as nuclear reactors, medical, research and industrial facilities, fuel cycle facilities, and radioactive waste treatment and storage. Examples of such sites include nuclear power plants (with two, four, or more reactors, waste stores, and other ancillary facilities) and nuclear research centers (with research reactors, critical assemblies, laboratories, glove boxes, stores of radiation sources, waste treatment and decontamination stations, etc.). These sites were generally developed over decades; changing priorities, stricter regulations, and stakeholder influences can result in a lack of coordination regarding the mission of single facilities and the whole site, as well as insufficient life cycle management. A lack of centralized vision will be more evident when one or more site facilities approach decommissioning and require the mobilization of technical, human, and financial resources in a short time, while other facilities remain in operation.

Closed-down units may quickly lose priority and attention by the site management. Plant refits are left incomplete; waste tanks are filled to capacity with contaminated liquids; work environments are left in a messy state; and possibly the Decommissioning Fund—often having been designed for a longer service lifetime—is not fully funded. With the site workers being diverted to the operating units, structural conditions in the shutdown plant may deteriorate quickly. Personnel losses will result from the plant shutdown, including many experienced workers, supervisors and managers, whose disappearance will be bitterly regretted later.

Regardless of the abovementioned issues, some favorable conditions (eventually resulting in reductions of costs and radiological impacts) may be produced by an integrated view of decommissioning at multiunit stations: for example, facilities of similar designs, the opportunity for sequential decommissioning, and the option of centralized waste stores on-site. Additional bonuses smart managers should not miss include the following: full decommissioning planning needs only to be done once and for all; the workforce is (initially) there and available for all the time needed; there is less handling of radioactive wastes; and central warehouses, equipment, and support facilities are usable across the whole site decommissioning project. In summary: the scale factor works at its best.

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Fig. 12.1 Ispra-1 reactor, JRC, Italy.
Photo by M. Laraia, 2014.

Fig. 12.2 Essor reactor, JRC, Italy.
Photo by M. Laraia, 2014.

By definition, interaction denotes a mutual or two-way action or influence, in this case between a decommissioning facility and adjacent facilities within a multifacility site. This chapter highlights both the impacts (actual or potential) from the decommissioning facility to nearby facilities and the impacts nearby facilities cause to the decommissioning facility.

Figs. 12.1 and 12.2 show two long-shutdown reactors at the European Union's Joint Research Centre (JRC), Ispra, Italy. JRC contains many nuclear facilities (gradually being decommissioned; the mission of the Centre was converted from nuclear to other applications).

12.2 The decommissioning strategies

The three main strategic options for decommissioning include immediate dismantling, deferred dismantling, and entombment (no further mention will be made in this report of this rarely used strategy). However, it is recognized that the actual decommissioning strategies in each country are likely to be less distinct because they are influenced by local and national circumstances. For example, it is not a rare event that a facility is partly dismantled, and the rest of the decommissioning work is deferred for many years.

The factors to be considered in determining decommissioning strategies—that is, how the choice between the three abovementioned options is likely to be influenced by national factors—are further complicated when a decommissioning project takes place in a multifacility site where other facilities are in decommissioning, under construction, or continue to operate. Typical situations are described in the following section.

12.2.1 Decommissioning two shutdown facilities on the same site

A large-scale example of several decommissioning projects on the same site is presented in Ref. [1]. This reference discusses the Hanford Interim Safe Storage (ISS) project and reviews the experience from four (F, DR, D, H) reactor sequential decommissioning projects. Each ISS task included the following: to remove all structures around the bioshields, seal all openings to the stores, and install a new roof and lighting and monitoring systems. Because the decommissioning planning and implementation was carried out in groups of two reactors, considerable synergies were reportedly realized. It appears that scheduling sequential decommissioning for similar units heightens efficiency within the decommissioning organization as they strive to optimize the work. However some disadvantages were identified.

12.2.2 Decommissioning one facility, while another on the same site is in operation

Typical questions electric utilities may be considering in decommissioning of a multireactor nuclear power plant include the following: does it make good business sense to shut down the entire plant? Vice-versa, could it better to shut down one unit and focus resources on operating the remaining units? If so, do you keep one operations department with staff managing both operations and decommissioning or do you assign different people to different units? Is the site physically split into two—the operating unit and the decommissioning unit? Will there be any use of the shutdown areas for the operating units? Will solid waste and liquids be left untreated? When will waste treatment be implemented?

If more than one facility is situated on the same site, it may be the best option to defer dismantling of the oldest facilities until the remaining facilities on-site reach final shutdown. The continuing operations will provide adequate safety and security also to the shutdown unit. There are many US reactors that were placed in a safe enclosure (SE) condition both to allow the operation of other reactors on-site to continue undisturbed and to later benefit from economies of scale in decommissioning several reactors in one project (Dresden Unit 1, Peach Bottom Unit 1, and Millstone Unit 1 all share this strategy; they are in SAFSTOR—the US term for SE—and each of their sites houses two more reactors in operation) [2].

To exemplify this situation, the following case is illustrated [3].

Indian Point Unit 1, NY, United States, was a small pressurized water reactor. It was permanently shut down in 1974. Units 2 and 3 are also pressurized water reactors each generating more than 1000 MWe. Since 1974, Unit 1 has been maintained in an SE mode. The initial strategy was to maintain Unit 1 in this condition until it would be dismantled along with Unit 2 at the time of expiration of the Unit 2 license in 2012. However, this strategy requires reconsideration because Units 2 and 3 licenses were extended to 2033. The following recaps the inspections and assessments carried out by the owner to assure that the prolonged SE of Unit 1 would not be a concern to Units 2 and 3 (Fig. 12.3).

The assessment of Indian Point Unit 1 was completed in 2005 and resulted in the following:

- The entire Unit 1 was evaluated for structural integrity and was found to be sound. The one structure requiring repair was the vapor containment concrete enclosure building shield wall, which had areas of spalling and exposure of several high tensile strength prestressing wire strands.
- Several areas with minor concrete cracks and spalling will require periodic monitoring.

Fig. 12.3 Indian Point Unit 2 &3 (Unit 1 invisible in this photo).
Reproduced with permission from US Nuclear Regulatory Commission, NRC photo file.

- The assessment noted several areas where rainwater/groundwater was leaking into the buildings through cracks in the ceilings, walls, floors, and their joints. If these processes are not controlled, they could trigger industrial safety hazards (slipping and electrical safety), cause the spread of contamination, and intensify degradation of the concrete structures.
- Several Unit 1 systems and components were "retired" in an undefined and undocumented manner many years ago. A full understanding of the technical bases and goals of these "retirements" had been lost. Although Unit 2 had safely operated in these circumstances for almost 30 years without any significant event, the retirement of a number of senior staff with the consequent loss of "tacit knowledge" might in the long term jeopardize the safety of the operating units. As a result of this appreciation, the assessment team identified the following needs:
- Clearly defined boundaries between Unit 1 nonoperational components and those components remaining active in support of Unit 2.
- A comprehensive evaluation of the risks associated with Unit 1 systems and components and their potential impacts on Unit 2.

The assessment team requested the following priority actions:

a. To expedite removal of Unit 1 spent fuel to dry cask storage.
b. Following fuel removal, clean and drain the Unit 1 spent fuel pools, fix contamination, and take measures to prevent water leakage.
c. Complete removal and disposition of radioactive resin and sludge from Unit 1 tanks.
d. Reduce deterioration to the containment enclosure building shield wall prestressing wire strands.

San Onofre NPP, CA, United States, is a case of active dismantling that commenced soon after final shutdown, while two more reactors on-site continued operation. When Unit 1 of San Onofre Nuclear Generating Station (SONGS) was retired in 1992, the operator initially planned to maintain the unit in SE until future decommissioning of Units 2 and 3. However, the decision was revised and decommissioning work started sooner than planned. This change was mostly based on the ready availability of San Onofre's skilled workforce, which could complete the project with limited reliance on external contractors. Besides, the Nuclear Regulatory Commission (NRC) then granted nuclear operators access to 3% of their decommissioning funds prior to actual decommissioning. These factors prompted the SONGS operator to earlier decommissioning of SONGS 1. San Onofre 1 became an active dismantling project that was largely completed in 2008. Some work remains to be completed for Unit 1 along with the eventual decommissioning of Units 2 and 3. SONGS 2 and 3 were permanently shut down in 2013 and the entire site is now in decommissioning [4].

At San Onofre several systems were shared by both the shutdown and operational units, including the following:

- The fire water system at SONGS 1, which was tied into SONGS 2 and 3.
- The site radio communication system, which had antennas and associated electronics in buildings throughout the whole facility, some of which were to be demolished.
- The meteorological tower, electricity, and communication lines, which passed through SONGS 1, as did the on-site emergency notification siren system.

The three units also shared a common security boundary with one protected area. Common entry, exit, and security forces are shared. Fig. 12.4 shows the congested SONGS site, tightly enclosed between the shoreline and the overlying motorway.

Fig. 12.4 San Onofre Unit 2&3.
Reproduced with permission from US Nuclear Regulatory Commission NRC file photo.

12.2.3 Decommissioning one facility, while another on the same site is under construction

The practice of building a new nuclear power reactor on a site where other nuclear facilities are already situated is becoming common, on account of the scarcity of new sites and the availability of infrastructure (electrical grid, cooling water, etc.) and other advantages (skilled labor, support services like catering, worker transportation, etc.). As of today a number of new builds are underway at old nuclear sites, for example, in the United Kingdom (Bradwell, Hinkley Point, etc.). Building new reactors at old sites is a national policy in the Russian Federation, with socioeconomic factors being essential in that policy. Due to the remoteness of certain sites in the Russian Federation, the limited mobility of the workforce, and the presence of population centers that developed purposely for the nuclear site, the job losses resulting from the decommissioning of one or more installations must be compensated for by the construction of new installations [5].

Another noteworthy case is the Humboldt Bay Power Plant (HBPP) in California. Unit 3, one of the first commercial nuclear power reactors in the United States, was shut down in 1976 and placed in SAFSTOR in 1983; and it is now completing decommissioning. What makes this project particularly challenging is that there are two aging fossil plants connected to the Unit 3 reactor building and a new nonnuclear 160 MWe plant under construction less than 30 m away. Besides, the site is very small with only about 12 ha available for use by the three power units, switchyard structures, the intake and discharge canals, two 10,600 m^3 fuel oil tanks, an independent spent fuel storage installation (ISFSI), parking lots, and several other buildings.

The problem is that new construction on a NRC licensed facility is normally intended to support nuclear operations and will not “outlive” the NRC license. If a structure were to remain after license termination, a final status survey (FSS) would be completed. But at HBPP, a non-NRC licensed facility was being constructed on soil that was impacted by operation of Unit 3 with future sampling of the soil underneath the footings being virtually impossible. There are two questions:

1. Can the licensee prove the soils beneath the new plant contain less residual activity than the release criteria approved in the license termination plan of the nuclear reactor?
2. Can the licensee prove that the soils and structures of the new plant have not been radiologically affected by the decommissioning process?

The approach given to solving these questions is described in detail in Ref. [6].

12.3 Integrated approach to site decommissioning

The term “synergism” refers to “the concept that working together or cooperating in a combined effort by sharing information and resources to accomplish some project tasks can produce more benefits than are achieved through independent and consecutive efforts” [7]. Synergies are required among construction, operation, and decommissioning activities because each phase is part of the overall site lifecycle management. The primary objective of decommissioning a nuclear facility is to remove (or reuse) the nuclear facility and to reduce any associated contamination levels to below those compatible with the future use of the site. This objective should be harmonized with the construction and operation of other nuclear facilities on-site. As a result, the successful design and implementation of decommissioning involves a number of common tasks including the following [8]:

1. Project management;
2. Risk assessment;
3. Materials and waste management;
4. Occupational safety and health;
5. Stakeholder involvement.

Identifying potential synergies in each of these activities (e.g., site infrastructure, workforce and supporting management systems) may make it possible to complete projects in a more timely and cost-effective manner.

The sections that follow define the common activities listed above and discuss the synergies between decommissioning and other site activities.

12.3.1 Project management synergies

For the purpose of this chapter, single projects stem from the broad strategy that identifies the needs and sequence for site activities, and the common elements in the planning and implementation of projects establish the synergies for cost, schedule, and reciprocal impacts between decommissioning and operation/construction activities.

12.3.2 Risk assessment synergies

Risk assessment refers to the potential exposures and risks to humans and the environment from radioisotopes or chemicals. Risk assessment is an essential component of decommissioning; it allows the responsible organization to minimize risks and define a proper end state for site reuse. It identifies and minimizes risks resulting from interactions between the decommissioning project and other site activities.

12.3.3 Materials and waste management synergies

Decommissioning of a nuclear facility generates large amounts of materials and waste that are quite different from the operational wastes (being generated on-site as well). Through careful planning and sequencing of dismantling, most of the waste can be segregated into inactive materials and low-level waste. Considerable reduction in volumes of radioactive wastes can be achieved through a tailored decontamination program, contamination control, reuse and recycle strategies, and other radiological and administrative provisions. In a multifacility site, interactions with operational waste management are crucial aspects.

12.3.4 Occupational safety and health synergies

An integrated approach to occupational safety and health maximizes the use of technical, human, and financial resources within the constraints imposed by the schedule for decommissioning completion, taking into account the other site activities.

12.3.5 Stakeholder involvement

Stakeholder involvement refers to the activities conducted during the planning and implementation of decommissioning that define and incorporate the priorities and concerns of parties affected, including trade unions, opinion groups, businesses, local communities, and environmentalists. The goal is to foster a climate that helps establish positive relationships between decommissioning organizations and stakeholders. The presence of other facilities on-site adds on the complexity of the stakeholder dialogue.

While project managers often think in terms of single projects, stakeholders may have a more general perception of the site that does not necessarily distinguish between operation and decommissioning. As a result, synergies may be obtained by having construction projects and operations tuned in with decommissioning projects to foster stakeholder involvement and contribution. Active involvement of stakeholders during the planning of projects may help in the identification of acceptable end states of the site, definition of priorities, and technologies. For example, stakeholders may have an interest in preserving structures (e.g., buildings) and infrastructure elements (e.g., roads). These concerns will have to be appreciated in decommissioning planning.

Integration of decommissioning projects and other site activities is not necessarily straightforward. Decommissioning timing is the prime factor that is affected by the presence of multiple facilities on-site. Some conflicting approaches may arise from a congregation of small facilities on a site, as illustrated by the following example from Cuba. A large hospital there presented a combination of (1) a Department of Nuclear Medicine, (2) teletherapy services (with high-activity sealed sources), (3) brachytherapy services (with different types of radioactive sources), and a (4) radioactive waste storage facility. In the event that one of these facilities must be decommissioned, the others had to continue to provide medical services. The responsibility for decommissioning activities could be somehow lost, because the radiation protection officer and the hospital administration continued to be responsible for the safety of the hospital services but would additionally become responsible for decommissioning planning and safe implementation. One issue in this case was prioritization of activities. Because economic resources were limited, the question arose as to where to spend the available funds: on medical services or the decommissioning of an old (unusable) facility? [9].

12.4 Technical aspects

12.4.1 Site layout

During decommissioning of a large facility, the traffic of vehicles in and out of the site will change—in type and in intensity. Vehicles may be given access to new routes. The local authorities and police may also require specific routes to be used and prohibit other routes [10].

It is also possible that the location of an adjacent plant will complicate access to the decommissioning plant for the delivery of decommissioning tools, installation of supporting building and services (e.g., a new waste store), or the removal of waste materials; or at least, it will make these activities more costly.

The detailed layout of the facility that was established at the design stage may have been changed during the construction if, for example, ground conditions are discovered that require certain parts of that facility to be relocated within a larger site. Care must then be taken to ensure that the impact of the relocation is fully considered in terms of decommissioning. Similarly, the decision to enlarge a facility may result in its being close to another facility that will be operational during the former's decommissioning, making it difficult. In such circumstances, it may be necessary to delay the decommissioning until the close operational facilities are also ready to be decommissioned, resulting in the need to maintain redundant plants, often for many years.

12.4.2 Shared structures, systems, and components

During facility decommissioning its configuration is constantly controlled to guarantee that design requirements specific to the status of the facility are fulfilled. Special attention should be given to configuration management (CM) due to the succession of ever-changing configurations in decommissioning. It should be also ensured that operating units are not impacted by the configuration changes in the decommissioning facility. A comprehensive treatment of CM (though not specifically addressing decommissioning) is given in Ref. [11].

To this end, attention is due to shared systems at multifacility sites during facility decommissioning including mechanical systems (service water, cooling water, and instrument air) or electrical distribution systems. It is vital to identify such interfaces to assure that the decommissioning of one facility does not affect the operation of a near facility and make the operating facility noncompliant with its design requirements.

Considering the decommissioning sequence of a facility at its design stage will allow effective isolation of its structures, systems, and components without impacting the operation of adjacent facilities.

For most facilities, changes in operation and layout have occurred during their operations phases, so it can be hard to ascertain end-of-life physical and radiological features. This case is typically more serious if the facility has been used for research (e.g., a research reactor), because this often has involved the use of new experimental apparatuses. To scope out the decommissioning project, it is useful to get a map of the decommissioning zone that also includes details of adjacent zones and services (drainage, electricity, ventilation, etc.). It is always good to ascertain (e.g., by way of visual inspection or laser scanning) that design drawings are consistent with as-built drawings. It can also be beneficial to interview senior workers because they may have undocumented knowledge. Fig. 12.5 shows the shut-down FR-2 research reactor at Karlsruhe Institute of Technology (KIT) in Germany. There are many nuclear facilities at KIT: after many years under SE, and use as a nuclear museum, FR-2 is now approaching the dismantling phase.

In a decommissioning case described in Ref. [12] a small nuclear facility failed to investigate the chances of leakage from the drainage system. This inattention became apparent when the regulator requested the drainage system be checked. The underground pipe was found to be broken and leaking, which required unplanned soil remediation.

Among shared systems, stacks are quite common and will be used here as an example of a dismantling project in a multifacility site. Stacks may no longer be required following shutdown of a facility, or they may be retained fully or partly operational in a SE phase or during decommissioning. Issues affecting how stack dismantling fits

Fig. 12.5 Outside of FR-2 research reactor, KIT, Karlsruhe, Germany
Photo by M. Laraia, 2014.

into the overall site strategy are comprehensively described in Ref. [13]. In particular, a factor affecting the selection of the stack dismantling technique is the (real or perceived) hazard that it could collapse onto adjacent facilities during dismantling. A discussion on the ongoing dismantling of the Garigliano NPP stack, Italy, is given in Chapter 1 of this book.

To cite one more example of shared systems, pipes are often placed in lined trenches below ground to link nuclear buildings or to discharge liquids off-site. In older plants, trenches had no liners. Over time, old pipes started leaking, so the adjacent environment was contaminated. The need for soil remediation can cause a considerable increase in the volume of waste—and an unnecessary increase of costs [14].

According to modern standards, piping should be normally routed above ground. If there is only a choice to have below-ground piping, it is critical that the piping be “doubly contained” (e.g., in waterproof trenches with sumps and hatches for easy access, or in a “doubly walled” configuration) to prevent soil contamination in case of leakage.

There are cases of process services that are provided by an external organization or sometimes by another company on-site—for example, fuel, steam, or nitrogen. In all cases, related contracts need re-negotiating at the time of decommissioning to take account of the changed conditions. The utility suppliers are often the only ones authorized to work on their equipment, piping, cables, etc. Agreeing to have rerouting and interim connections for changes in flow and composition limits for discharges may be necessary. It is also possible that utilities pass through the site to other users: whether this should continue during and after decommissioning calls for investigation and renegotiation with all parties involved [10].

12.4.3 Waste management

Waste management is an intrinsic part of decommissioning, and the latter cannot be safely and cost-effectively completed without the availability of full waste management infrastructure. This often implies that the decommissioning of a nuclear facility should be preceded by the decommissioning, refurbishment, or construction of dedicated radioactive waste management facilities. A case in question is the Vinca nuclear research center, Serbia, where an IAEA technical assistance project on decommissioning of a research reactor has been in place since the early 2000s. A European program managed by the IAEA was launched a few years later, consisting of the following tasks in support of reactor decommissioning (some other tasks are aimed at the more general upgrading of Serbian infrastructure and have not been reported here) [15]:

1. Repatriation of the Serbian spent nuclear fuel to the Russian Federation
2. Equipping of the radioactive waste processing facility
3. Management of sealed radioactive sources
4. Decommissioning of Hangar No. 1 (a radioactive waste store)
5. Radioactivity survey at the Vinca site
6. Operation of the radioactive waste processing facility
7. Support to the Project Management Unit (PMU)
8. Decommissioning of the underground radioactive liquid waste tanks
9. Decommissioning of the spent fuel storage pond

Arrangements for the management of waste and waste records should be in place within the decommissioning organization. In a multifacility site, such arrangements should be compatible with the management of waste arising from other site facilities. Waste may or may not be stored within the decommissioning facility or on-site during the various phases of decommissioning depending on factors such as availability, adequacy, and capacity of on-site stores or disposal facilities, long-term waste projections, or regulatory positions. Where waste is stored it should be safely managed. If on-site waste storage is not allowable, arrangements should prevent undue accumulation of waste and waste disposition routes should be established with no delay.

During the decommissioning period, some waste will be generated, possibly in much larger amounts than during operation. A system should be in place for the collection, characterization, sorting, conditioning, and storage of radioactive waste. The radioactive waste will consist of items such as filters, discarded equipment, concrete debris, steel scrap, and general garbage. Regular shipments should ensure transport of radioactive waste to a centralized storage or disposal site.

The decommissioning waste will be either radioactive or inactive waste. For the inactive waste the normal local waste collecting services can be used to dispose of the waste. Waste clearance provisions should be in place to segregate radioactive waste from inactive waste.

Interference between decommissioning and operational waste should be taken into account in the planning and implementation of site activities. It may be due to the following factors [16]:

- Rate of generation (large amounts of decommissioning waste produced only during specific phases of decommissioning versus more regular production during operation)
- Unusual physical-chemical nature of certain decommissioning waste [17]
- Need to manage unusually large components during decommissioning
- Larger amounts of waste eligible for clearance.

Regarding airborne and liquid radioactive emissions, some regulators may promulgate a stricter site “discharge formula” on account of the (typically) reduced discharge need from the decommissioning facility.

When a plant is in operation, rainwater is usually arranged to flow separately from the process effluents and is typically released into watercourses. The separation of the water collection systems can cease to work, however, during decommissioning, if drains overflow or building walls, roof claddings, or other barriers are improperly removed exposing contamination to environmental agents. If so, radioactive and chemical contamination may end up in watercourses that were not planned to receive these contaminants [10].

Nonradioactive emissions occur mainly as the following:

- Noise;
- Air contamination.

Both occur especially during large-scale demolition. The noises and clouds of dust and/or smoke can be a major inconvenience to site neighbors. It is therefore critical to circulate timely information to adjacent facilities, and to closely monitor activities so as to minimize the inconvenience.

Regarding radioactive gases, one interesting case was reported during Moata decommissioning. Moata was a small Argonaut reactor in Australia. It was installed in a building adjacent to an accelerator for C-14 dating. Moata had a relatively large amount of graphite whose C-14 inventory could create a serious interference to the sensitive accelerator. To minimize the risk, a containment tent with HEPA filtered air extraction remained installed around the reactor during the whole dismantling [18].

12.4.4 Area and component reutilization during decommissioning

Site management may consider alternatives for the shutdown unit areas. The management may view the shutdown as an opportunity for new found areas for the operating unit's growth (e.g., system modifications, staging or storage areas). For example at Dresden station the Unit 1 (shutdown) High Pressure Coolant Injection Building was reused for the Station Blackout Diesel Generators and support system for the operating units. New space availability that may already be heated and serviced becomes a relief for congested sites. However, careful planning and reviews by the utility accountants and decommissioning personnel must be made. Capital expenditures to a shutdown and retired area of the plant can have implications for the decommissioning fund and require regulatory approval in that the configuration of both the shutdown and the operating unit will change. Proper accounting for the shutdown space utilization would include transfer of the area to the operating unit inventory [19].

A potential saving of resources in a multifacility site management is the reuse of components from the shutdown facility in similar facilities on-site. Such is the case at the Metsamor NPP in Armenia, where the shutdown unit is being "cannibalized" to provide components for the twin operating unit [20].

12.4.5 End state

It is generally recognized, and consistent with international recommendations, that the normal end state of a decommissioning project should be the unrestricted release of the facility and its site. However, if the decommissioning facility is co-located with operating facilities, achieving unrestricted release could be impractical or prohibitively expensive. This is due to the built-up contamination resulting from former operations. A similar case may occur if the areas adjacent to the decommissioning facility are contaminated by past releases or radiological incidents: if so, decontaminating one facility to unrestricted release, while surrounding areas are still contaminated, may turn out to be a futile exercise, due to the possible and hard to control recontamination of the already decontaminated area. Under such circumstances, it may be more appropriate to decontaminate the decommissioning facility only to an acceptably interim status of restricted release and defer completion of decommissioning and release of the whole site to a time when no new contamination is expected to be generated.

It is however possible that peripheral parts of a site are cleaned up to unrestricted release levels and delicensed, while the rest of the site remains under institutional control. To implement this option, it should be demonstrated that recontamination of delicensed areas is unrealistic. The Harwell and Winfrith sites in the United Kingdom prove the case in question [21,22].

As a factor supporting the reuse of decommissioning sites for new builds, some sites are contaminated to a level that precludes unrestricted release: the best option might then be to preserve the site as a nuclear site, which would allow some residual contamination. Sellafield, United Kingdom, could be a typical case in question.

12.4.6 Ground contamination

Ground contamination is another consideration for cross-facility impacts in a multifacility site. Surface and underground contamination may spread quite a distance beyond the boundaries of a single facility or decommissioning project: the implications require careful consideration of technical (scoping surveys, soil sampling, environmental remediation, waste management, clearance criteria) and legal aspects (liabilities, stakeholder involvement). Ground contamination dictates the decommissioning project be broadened to a remediation project, and these two aspects should be addressed in an integrated manner. IAEA guidance on this subject can be found in Ref. [8].

The ground can become contaminated during the operations life of a plant, but there are also ways whereby this can happen during decommissioning. Common events are spillages when emptying process tanks or removing pipelines, overflows when drains get plugged by demolition rubble, and leaks from floors that have been inadvertently damaged during decommissioning.

12.4.7 Safety assessment

The approach to safety assessment (for workers, the public, and the environment) in decommissioning projects is quite different to that established for operations. This is due to the dismantling of barriers that are essential to safety during operations and due to conditions of the work environment and plant configurations being constantly altered during decommissioning. A decommissioning plan should include an evaluation of the potential radiological impacts during planned activities or caused by any credible incidents. The IAEA published some reports on safety assessment for decommissioning, for example, [23]. It should be noted that a multifacility site may induce additional hazards to the facility being decommissioned, or vice versa.

A fire event will be mentioned as an example. The risk of fire in a decommissioning facility can be limited by removing combustible materials and ignition sources as far as possible during the operation-to-decommissioning transition. However, this may not completely rule out the risk of fire, especially fires that originate outside the facility (e.g., from adjacent facilities). It should be noted that the firefighting plan available for the operational phase must be amended because building layout, water supply, access routes, etc. may have changed in the course of decommissioning—especially in a multifacility site. In some countries, during an SE phase, an on-site fire brigade is no longer required, while in other countries firefighting requirements are even increased due to the lack of the on-site workforce that can at least launch an early warning. For multiunit sites the decommissioning facility can benefit from the on-site fire brigade so long as it remains there.

12.5 Organizational aspects

One organizational approach deemed essential in a multifacility site is to establish a separate decommissioning staff for the permanently shut-down unit as soon as possible. See the Ignalina case in Section 12.5.2. This approach would be significant for three reasons:

- It enables the site staff to primarily focus on the remaining operating units
- It provides dedicated resources to the safe and timely decommissioning
- It provides assurance that the shutdown unit activities will not impact the operating units

The decommissioning workforce is recognized as a separate group or department on-site and may or may not have technical personnel who support both the operating units and the decommissioning unit. Still there will be support personnel on-site that function for both the operating units and the shutdown unit such as the security force, warehouse personnel, supply management personnel, and administrative (e.g., record-keeping, food service) personnel.

However, there is an alternative organizational approach that recognizes the importance of merging inputs from the operational part of the site into the decommissioning part—and vice versa. See the Loviisa case in Section 12.5.2.

Because regulatory requirements, as well as organizational functions, will be different in decommissioning areas from those in operation, it is desirable to physically differentiate areas. Fencing off is the normal approach to this issue [10]. However, physical separation is easier said than done. First a preliminary scoping survey should ascertain that there is no cross-boundary contamination, including underground media.

12.5.1 Personnel profile

When a nuclear facility ceases operation, it cannot be abandoned. The multifacility site is still the responsibility of the owner, who must ensure safety, decommission the shutdown facility(ies), and ultimately release the site to a greater or lesser extent. Each of the transitions—from operation, to shutdown, to dismantling, to site release and redevelopment—may take many years. At each transition, the organization in charge must retain the knowledge and the skills to hold the license and own the site—which still contains operating facilities.

Strategic decisions about each transition will directly influence the human resource strategy because the pressure to reduce staff costs and numbers will grow. As the end of the operational period approaches, the staff may feel uneasy about their future, and they may seek to leave because they do not find the decommissioning work attractive, or they may be looking to more secure employment prospects. It is frequent that the more valuable staff leaves first.

During each of the transitional periods, the number of staff and the skills needed to support the whole organization must be maintained, subject to changing demands. The needs should be determined by an assessment of the organizational functions—including both decommissioning and operating units. It is therefore imperative that the strategies for site management enable a long-term human resources plan to be developed [24].

A few consequences from this optimized approach are given in the following. When one or more facilities at a multifacility site reach a dormant state, the former operations staff assigned to those facilities is often redistributed to the facilities that are still in operation. The experience of this staff can be effectively used should any technical problems occur with the shutdown facility. It must be avoided that alarms or other indicators of deteriorating conditions coming from the dormant facility are ignored, due to higher priority being given to the facilities that are in operation.

The same caveat applies to maintenance issues. Although giving priority to maintenance work at the facilities in operation makes sense, care must be taken that maintenance to the shutdown facility is not ignored. Poor maintenance can easily lead to premature degradation and in the longer term incur safety concerns.

12.5.2 Organizational structures (examples)

One case of interdependent facilities simultaneously in different phases occurred at the Ignalina NPP (INPP) site, Lithuania. The decision to shut down Unit 1 at the end of 2004 and Unit 2 at the end of 2009 meant that decommissioning at Unit 1 would commence in parallel with continued station operation.

This prompted INPP top management to establish two organizations, one for station operation (Technical Directorate, INPP TD) the other (Decommissioning Service INPP-DS) for decommissioning. INPP-DS initially lacked experienced personnel with the engineering, project, and commercial skills to effectively manage the decommissioning work. Consequently, a PMU was established at the end of 2001, within the INPP-DS, which was managed by a consortium (consultant) from the UK, Belgium, and Sweden. The consultant's primary objective was to instill decommissioning expertise to INPP with a strong emphasis on training and directing INPP-DS staff (Lithuanian) to new tasks. As INPP-DS staff developed the necessary competences, responsibilities were gradually transferred from the consultant to INPP-DS. In 2006, after four years of PMU operation, the overall management was finally handed over to INPP-DS, with the consultant performing only specific roles under the INPP-DS umbrella. This model of marrying a consultant with INPP-DS staff worked well. Its success was based on good working relations, across-the-board training, and a tenacious mission to transfer motivation, knowledge, and responsibilities to INPP-DS. Another major organizational issue for INPP regarding decommissioning was the relationship between INPP TD and INPP-DS (i.e., between the two Ignalina reactors). While the INPP-DS had overall responsibility for decommissioning, most of the resources and knowledge stayed with the INPP TD, whose objective was station operation. Conflicting demands on the staff's time, priorities, and schedules created many new challenges to the site management. This situation was eventually solved by establishing clear lines of responsibilities and by defining what specifically was required from INPP-DS and INPP TD [3].

Loviisa Nuclear Power Plant (NPP) is located about 100 km east from Helsinki, Finland. The site includes two VVER-440 type pressurized water reactors. The plant is operated by Fortum Power Division, which has about 600 employees on-site. Loviisa units 1 and 2 started operation in Feb. 1977 and Nov. 1980, respectively. The current operating license of Loviisa NPP is valid for 50 years, in other words, 2027 (Loviisa 1) and 2030 (Loviisa 2) (Fig. 12.6).

A basic principle of the Loviisa preliminary decommissioning plan is that the power plant's own personnel will be responsible for project administration linked with the decommissioning, the planning work, operation of the necessary processes, and certain decommissioning tasks that require familiarity with the plant and specific expertise. Other clearly definable tasks related to decommissioning will be contracted out separately.

As the decommissioning progresses, the operating organization of the Loviisa NPP will change stepwise to a decommissioning-only organization. When the preparatory phase of the decommissioning of Loviisa 1 begins, Loviisa 2 continues to be in full operation. The organization of the Loviisa 1 preparatory phase (system maintenance, waste treatment, defueling, general decontamination, etc.) will mostly comprise the operations personnel of Loviisa 1.

The staff of the organization required for the preparatory phase has been estimated at 189 people. Some of the people will be in charge of tasks associated with both the operation of Loviisa 2 and preparations for the decommissioning of Loviisa 1. In the preparatory phase, the most important contracts to be carried out by external

Fig. 12.6 Bird's-eye view of Loviisa NPP's two reactors.
Reproduced with permission from International Atomic Energy Agency. J.P. Tuunanen, T.E.E. Eurajoki, Decommissioning Planning During the Operation of the Loviisa NPP—Planning, Management and Organizational Aspects. Planning, Management and Organizational Aspects of the Decommissioning of Nuclear Facilities, IAEA TECDOC No. 1702, IAEA, Vienna, 2013, PP. 77–87.

contractors will include construction of the access ramp outside the reactor buildings, construction of the segmenting and packaging station for the decommissioning waste, and extension of the repository for decommissioning waste.

When the actual dismantling of Loviisa 1 begins, the organization will be changed so as to meet the requirements set by the decommissioning.

Upon cessation of Loviisa 2 operations, the transition from the operating organization to the decommissioning organization will be similar to Loviisa 1. The maximum number of the decommissioning staff on-site will be almost 430 people. Three distinct peaks of person-hours can be recognized, namely, (1)the beginning of the preparatory phase of Loviisa 2, (2) the start of the active decommissioning of Loviisa 2, and (3) the dismantling of the auxiliary systems after all spent fuel has been removed from the plant [25, pp. 77–87].

12.5.3 Site responsibility

The following is one example of organizational scheme (e.g., typical of a nuclear research center) to make sure that decommissioning responsibility for one or more facilities in a multifacility site is assigned taking into due account interdependencies with other site facilities. Multifacility sites need to be organized and structured with dedicated site-wide responsibility for overall site decommissioning. The main function of such a group should be to establish a site-wide decommissioning policy, strategy, and program as well to assess decommissioning cost and to ensure that decommissioning funds are or will be available at the appropriate time. The decommissioning group should also be responsible for the coordination and execution of decommissioning projects on-site with the appropriate inputs and involvement of operators of the facility to be decommissioned, as well as of the operators of other facilities that may be impacted by a specific decommissioning project (interface management). The operators of facilities are responsible for decommissioning planning (jointly with the site decommissioning group), shutdown, and execution of at least the initial phases of decommissioning involving the removal of the bulk of the radiological and other hazardous material inventories. The operators of facilities are also responsible for obtaining authorization for shutdown and initial decommissioning activities. At a predetermined point the facility, within clearly defined boundaries, is transferred to the group responsible for decommissioning.

Justification for the establishment of an organizational structure that is responsible for decommissioning on a multifacility site can be based on the following factors:

- Consistent interpretation and execution of the site decommissioning plan and ability to coordinate and prioritize decommissioning projects on a site-wide basis.
- Consistent approach in terms of decommissioning project management.
- Consistent interpretation and application of site-wide decommissioning management system requirements and project evaluation and approval processes.
- Site-wide record of decommissioning liability and management of financial aspects associated with decommissioning, including cash flows for all site facilities.
- Consistent criteria and application of material clearance criteria.
- Consistent management of decommissioning waste, ranging from estimates of waste generated to disposal provisions (some material and waste handling options are only viable if considered in terms of the overall site-wide needs e.g., a centralized size reduction facility).

- Consistent involvement in the operator's initial plans and management of decommissioning interfaces among operators and between the decommissioning group and operators.
- Consistent application of methodology: for example, characterization and technology selection criteria.
- Establishment of a skilled workforce that can assist with various decommissioning projects.
- Operation of corporate facilities that support decommissioning: for example, decontamination and waste processing facilities.

12.6 Regulatory approaches

The licensing and regulatory management of decommissioning within a multifacility site exhibits certain unusual aspects. On the one hand a nonprescriptive regulatory framework that leaves room for flexibility through interpretation could result in inadequacies and inconsistent decommissioning management. On the other hand, prescriptive approaches to decommissioning are typically formulated for single facilities and may disregard interactions between adjacent facilities on-site.

There are several observations regarding regulation of two co-located units where one continues to operate and the other is decommissioned. Firstly, doing deconstruction next to an operating plant would create some difficulties related to (1) shared systems, (2) specific risks of dismantling activities (e.g., fire hazards), and (3) coordination and management. Dismantling dual units at the same time is generally seen as creating fewer problems. Secondly, to decommission one unit while operating a co-located unit may result in low priority being given to the decommissioning activities. The Dresden-1 case quoted in Ref. [26] can be considered an example case. While Dresden-1 was officially retired in 1984, Dresden-2 and -3 remained in operation (and are still operational today). Even though various decommissioning activities were accomplished at Dresden-1 from 1978 to 1993, there was a gradual deterioration in systems and structural condition. In Jan. 1994, a service water system pipe freeze resulted in 200 m^3 of water being leaked in the containment sphere. The NRC inspection team identified a pattern of declining management oversight on the shutdown unit.

By contrast, the existence of a co-located operating unit can be viewed as improving the availability of resources and the continuation of a safety culture at the decommissioning plant. Other observations about operating one unit co-located with a decommissioning unit are that plants may experience problems with a lack of communication, poor quality assurance (QA) at the decommissioning plant, and incomplete checks (in one case, audits that were supposed to cover the whole site were only performed at the operating unit) [27].

In some countries, facilities on multifacility sites were in operation before legal and regulatory frameworks were fully implemented. Typically, licenses were granted to individual facilities as they came into operation and interactions between site facilities went largely unnoticed. Later upgrading of the regulatory functions, safety, and QA standards and the need to estimate decommissioning liability costs have resulted in site-wide decommissioning arrangements being reconsidered.

A more difficult factor to regulate is safety culture. Electric utility deregulation is the driving force pushing the energy costs lower and the plant capacity factors higher.

For the maintenance and operation personnel this means shorter, smaller scope outages and more online maintenance—resulting in less time and lower priorities for the shutdown unit on-site. In a competitive environment, this "operational focus" is mandatory; however, the site culture and personnel staff's attitude will need to be one of appreciation that there are still requirements and responsibilities for the shutdown unit. Sloppy attitudes toward the shutdown unit may have to be corrected through training, site awareness sessions, and most importantly by visible management support for the shutdown unit. These activities can be monitored by the regulators, but safety culture is an elusive factor, which may demand more refined investigations.

12.6.1 Security

In a multifacility site the decommissioning facility can be guarded by the crew that guards the whole site. This will not lead to extra costs because these people are on-site anyway. A point in question here is whether or not the decommissioning facility is fenced off from the other facilities. At multifacility sites one can even consider leaving existing doors and access points to the decommissioning facility in place.

Access for decommissioning purposes should be limited to the staff of the decommissioning facility or other authorized personnel. To make sure that only qualified staff enters the facility an identification system should be in place. Contractors should be clearly identified and duly allowed to enter the buildings under decommissioning.

To limit the number of special security doors for access to a facility under SE it may be advisable to remove all existing doors, windows, and other openings during the operation-to-decommissioning transition and have them walled. Preferably only one access point should remain. This access point should be reinforced with a suitable door, including intruder detection. Depending on the facility layout and local regulations it may be necessary to have one or more emergency exits from the SE in place. The emergency doors should be easy to open from the inside, while opening from the outside should be made very difficult.

12.6.2 Environmental monitoring

The environmental monitoring program should be proportionate to the hazards residing on the site at any given time. During the transition to decommissioning, it is advisable to keep some components of the former environmental monitoring program in place, such as gamma dose measurements in air and sampling radionuclide deposition on grass and water. This is because the decommissioning work might lead to new release pathways. As soon as decommissioning is underway for all facilities on-site, the environmental monitoring program may be significantly reduced. After a trial period, assuming that the decommissioning project has gone smoothly without incidents or uncontrolled releases, a further reduction of environmental monitoring can be considered, especially if all facilities have reached a passive SE condition.

In general, off-site environmental surveillance will be typically controlled by requirements associated with facilities still operating on-site.

12.6.3 Independent operators

It is a common case that facilities situated on the same site are managed by different operators. If so, the facility interactions described in previous sections can be even more problematic. For example, reaching an agreement between facilities on staff transfer or reutilization of idle areas can be harder if the facilities have different interests and report to different managers. Even the tackling of cross-facility safety issues may receive less attention insofar as such issues extend beyond a facility's borders into the realm of other operators. Therefore, some form of site coordination is imperative. Under such circumstances the role of the regulatory body as an independent party may be essential to ensure an equitable treatment of such safety issues on either side of a facility's boundaries.

12.6.4 Knowledge management

The loss of information at any stage of a facility's life—and especially over a decades-long decommissioning project—deprives people, at later stages, of knowledge that could be critical to safe, timely, and cost-effective completion of the project. It is costly to go through the learning process again, with a risk of impending incidents, project delays, and increased regulatory surveillance. In some cases, it may be impractical to re-construct information. Therefore, it is important to establish a methodology at an early stage in the decommissioning process to capture, digest, and retain knowledge about decisions, strategies, and the rationale behind these decisions, so that those who were not contributing to the original decision-making process can follow on. Relevant information should be documented and properly stored to provide objective data for later work. This methodology will ultimately serve as an important source of information for all site management activities, including, but not limited to, decommissioning.

Knowledge management (KM) should also aim to ensure that reliance on "tacit knowledge" is reduced, and hence foster the organization's robustness against changes of personnel—an inevitable consequence of transitioning from operation to decommissioning and through the various phases of decommissioning. KM strives to preserve knowledge about plant design, construction, operation, and maintenance, so that the knowledge can be transferred to the next generation of plant personnel. In this regard, decommissioning at a multifacility site offers the opportunity to transfer decommissioning-related knowledge to the "neighbors." Decommissioning a single-unit site would be more problematic in terms of storing and retrieving useful knowledge.

The IAEA has provided guidance on the establishment of decommissioning-oriented records and their preservation for long periods in two technical reports [24,28]. Like for most literature in this field, the focus is on single-unit projects. It can be expected that in multiunit projects the records relevant to the one facility being decommissioning be extracted and selected from a broader database including other site facilities. This process can entail challenges additional to the selection of records from one facility's database. Moreover, the record-keeping functions for the decommissioning facility may have to be clearly separated from those associated with remaining operational facilities, but links to other facilities should be available and activated as needed.

12.6.5 Asset management including postdecommissioning site reuse

Asset management is the business discipline of monitoring and tracking the life cycle of the assets of an organization. The life cycle of an asset begins with its procurement and financing and extends through its maintenance, repair, and upgrades, until the asset's eventual disposition (i.e., from design through decommissioning).

An asset is defined as an economic resource, tangible or intangible, that is expected to provide benefits to a business. The primary assets for a nuclear organization managing a multifacility nuclear site are the nuclear facilities per se and their staff. It is therefore necessary to ensure that these assets are properly managed, which includes investment to maintain and improve them in order to achieve the optimal life of the site (in availability, productivity, and costs) from design to decommissioning of the last remaining facility on-site.

Finally, when a nuclear facility has been decommissioned, the land and/or buildings will be put to a different use. New consents and permissions are therefore needed, which is the responsibility of the new operator or owner. It is important to ensure that the presence of the original facility was not an essential feature of permissions to build new facilities (nuclear or nonnuclear) on the same or adjacent sites.

There may be situations where the facility owner may request that parts of the site be removed from the nuclear license before decommissioning is complete. The regulator will want assurances that such portions of the site have been thoroughly surveyed, that they meet the site release criteria, and that any new activities do not adversely affect decommissioning. A special case would be where the owner or other organization desires to use a portion of the site for a new, nonnuclear electrical generating facility (sometimes called repowering the site). See the Humboldt Bay 3 case in Section 12.2.3. In this case the regulator will want assurances that any new construction will not interfere with decommissioning and that any stored material such as chemicals or fossil fuel storage tanks will not present a hazard to the safe storage of nuclear fuel or materials on the site [29].

Enhanced land profitability can be due to factors such as expansion of near cities; establishment of attractions such as museums, business parks, etc.; or the use of existing infrastructure for new installations. In the United Kingdom, while there are sound financial grounds for profitably redeveloping a few areas located within commuting distance of London (Harwell, Winfrith) the majority of nuclear installations are dispersed widely along the British coastline. However, existing nuclear sites could offer an opportunity for new builds. In Jun. 2011, subsequent to extensive grounds and building testing, half of the Oldbury site was delicensed by the UK Office of Nuclear Regulation (ONR) and the land was proclaimed free of radiological risks and suitable for reuse. The released part of the site includes a popular countryside path and an information center. Part of this delicensed land will be used for a new nuclear power plant. The 36 hectares remaining under nuclear license contain the site's old plant, namely the two Magnoxes and other plant infrastructure [30]. The Nuclear Decommissioning Authority (NDA), as the responsible entity, has adopted the policy of maximizing the commercial value of decommissioning sites in the United Kingdom—either for nuclear or nonnuclear reuse—as a way to mitigate the growing cleanup costs. Valuing sites for new builds is hard, but in general the scarcity of new nuclear sites will increase the worth of existing ones.

12.7 Costs

There is no specific guideline on how to apportion costs in a multifacility site decommissioning program. The following list includes, but is not limited to, items that will need to be distributed among various decommissioning projects or operational activities on a given site:

- Decommissioning of shared systems
- Installation and operation of supporting facilities whose usefulness extends beyond one decommissioning project
- Research and development (R&D achievements may go far beyond the project that originated R&D needs)
- Site assets that may belong to different projects and activities
- Stakeholder involvement
- Security

In estimating the near simultaneous decommissioning of co-located reactor units there can be opportunities to achieve economies of scale by sharing costs between units and coordinating the sequence of work activities.

There will also be schedule constraints, particularly where there are requirements for specialty equipment and staff, or practical limitations on when FSSs can take place. A detailed analysis of decommissioning costs for the Indian Point NPP is given in Ref. [31,32]. See Section 12.2.2 for a brief description of the three reactors at Indian Point (IP-1 shutdown, IP-2 and -3 still in operation). The estimate for IP-3 considered the following:

- Savings will be achieved in program management, especially with costs associated with the more senior positions, from the sequential decommissioning of two identical reactors. The estimate assumes that IP-2 is the lead unit until removal of its reactor vessel and primary system, when IP-3 takes the lead for its own reactor vessel and primary system dismantling. Costs for the senior staff positions are only accounted for in the lead unit.
- It is assumed that IP-3 will not transfer spent fuel directly from its pool to the ISFSI. Instead, the cost estimate for IP-3 includes the transfer the fuel from the IP-3 pool to the IP-2 pool, where it would be packaged for storage at the ISFSI.
- Decommissioning on a multiunit site needs to be coordinated at the site management level. As such, demolition and soil remediation, following the primary decommissioning phase (removal of major radiological items), are carried out as a site-wide activity.
- Plant costs, such as ISFSI operations, security, emergency response fees, regulatory fees, corporate overhead, and insurance, are shared across all the reactors.

A comprehensive—if old—NUREG report [33] (and its supplement [34]) reviews in detail costs and radiation doses of decommissioning reference reactors in a multifacility site versus reference single facilities. The cost assessment given by this publication can be used to identify cost items rather than actual figures. The general conclusion is that there are savings both in costs and radiation doses in multifacility scenarios.

12.8 Conclusions and recommendations

Management of multifacility sites should combine facility-specific decommissioning strategies in an integrated effort to optimize the site management of decommissioning. The overall approach should be the establishment of site-wide decommissioning management with organizational arrangements, management functions, and processes focused on decommissioning. Strategic objectives and action plans need to be developed around the following main focus areas:

- Site-wide system for the planning and management of decommissioning throughout the lifecycle of all facilities and beyond (the redevelopment phase).
- Site organization that includes a group with overarching responsibility and expertise for decommissioning and liability assessment.
- Early identification of interfaces between facilities whether operating or shutting down, including physical interdependencies, organizational schemes, personnel resources, and schedules.

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Recent experience in environmental remediation of nuclear sites

13

P.M. Booth
Hylton Environmental, Cheshire, United Kingdom

13.1 Introduction

Contamination of the ground and groundwater on nuclear sites might result from historical as well as current practices and incidents. Such incidents might include leaks from buildings and tanks, spills during the transportation of materials, leaks from historical waste disposal trenches, and as a consequence of cross-contamination from poorly designed boreholes. Due to the potential risk to human health or the environment from such contamination it may be necessary to remediate specific areas of the site in order to control or eliminate this risk.

The IAEA has defined remediation as "the process whereby any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans" [1].

Because of the complex and historical nature of many nuclear sites and the wide variety of materials handled, any potential contamination may be radiological or non-radiological in nature, and often a combination of both.

As a nuclear licensed site moves toward the end of its lifecycle decommissioning activities are likely to accelerate, although it should be recognized that decommissioning is not undertaken exclusively upon a site's closure. There are examples where decommissioning activities will occur in parallel to ongoing site operations, especially at sites with a long historical legacy (Sellafield in the United Kingdom for example).

Remediation is invariably an expensive exercise so it is necessary to understand the drivers for carrying out such work as well as the potential options available to meet any required remediation or dose targets. The drivers to undertake remediation might include site delicensing, meeting a desired end state, offsite migration of contaminants, stakeholder pressures, or it may form part of the site's overall decommissioning strategy. Adopting a sustainable remediation approach, especially in countries with limited available funding, might be necessary. In such instances it is important to set and agree upon required cleanup targets prior to the commencement of any work so that regulatory and, in many instances, public approval can be acquired. A remediation program should be well planned and designed around a sound understanding of the site and its immediate environment, usually though the prior production of a conceptual site model.

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Understanding a site's lifecycle and how the two complementary activities of decommissioning and remediation might interact is therefore important. As mentioned previously, a remediation program might form part of the decommissioning or site release strategy but it may also be required as a standalone activity without any decommissioning taking place at the site. The timing of any remediation program therefore needs to correlate with both the drivers and the other potential activities being carried out at the site.

While the primarily focus of this chapter will be to highlight examples of where remediation has been carried out on nuclear licensed sites that are also undergoing decommissioning it will also discuss why in some instances remediation is currently being undertaken without the presence of decommissioning activities.

13.2 Environmental remediation within the decommissioning lifecycle

A nuclear site has a well-established lifecycle commencing with planning/design/construction, through operation and then ultimately decommissioning as it moves towards its eventual closure. As Fig. 13.1 shows, environmental remediation can take place throughout the operating lifetime of a site and often during or after decommissioning.

Decommissioning itself usually takes place after the cessation of site activities, but because many sites have a long operating lifetime it is not uncommon to see decommissioning activities being carried out in parallel with some of these operations. The Sellafield site in the United Kingdom, for example has a wide range of legacy facilities that will take time to decommission. However, there is the potential that if they are left untouched they will result in some safety and environmental challenges in the near future. In instances like this it is undoubtedly prudent to implement some focused decommissioning as soon as is feasible.

The decommissioning process also revolves around a lifecycle with the following types of activity shown in Table 13.1 below.

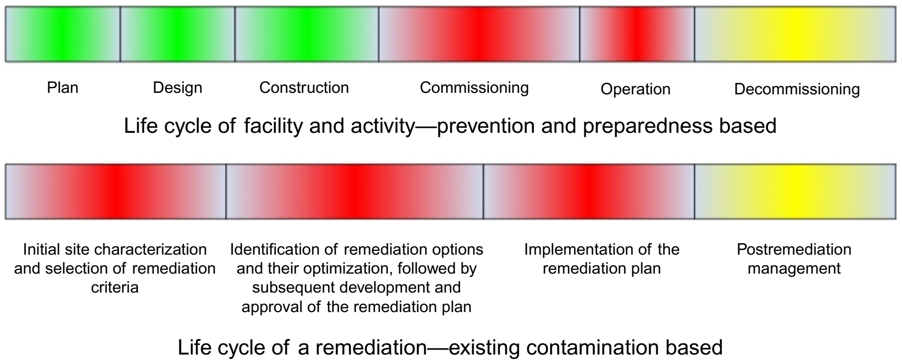

Fig. 13.1 Remediation within a site's lifecycle.
Figure courtesy of the IAEA.

Table 13.1 Decommissioning activities

Facility stage	Decommissioning activity
Design, construction, and start-up phase	Initial Decommissioning Plan
Operating Phase	Update Decommissioning Plan
	Finalize Safe Enclosure Plan
	Prepare Shutdown Plan
Transition Phase	Source term reduction and waste conditioning
	Prepare Site Preparation Plan and S&M Plan
Preparation Phase	Site preparation and initial dismantling
Deferred Dismantling Period	Update Final Decommissioning Plan
	Surveillance and maintenance
Decontamination and Dismantling Phase	Decontamination and dismantling activities
Final Phase	Final survey and license termination

Many factors need to be considered when determining the timing of environmental remediation within both the site and its decommissioning program lifecycles. In many instances, before the advent of physical decommissioning and demolition activities, it might be necessary to demonstrate that an understanding of any surface or below-ground contamination is already in place. This baseline understanding allows a site to verify that any subsequent decommissioning activities are not leading to further ground contamination. A soil sampling and/or groundwater monitoring program followed by the production of a conceptual site model is invariably utilized to provide such verification.

There may, in some instances, be very little reason to perform environmental remediation adjacent to or under a facility until the entire decommissioning process is complete. The decommissioning activities themselves might cause ground contamination, which will then necessitate a further phase of remediation. If a facility is still standing there are likely to be a number of access issues. Firstly, an inability to gain access underneath or adjacent to a facility will reduce the confidence in the overall site characterization and thus potentially lead to an incorrect remedial approach. Secondly, most if not all facilities have a safety case associated with them, which might preclude certain activities like the drilling of boreholes, the injection of materials, or the utilization of remedial techniques that cause vibration.

The actual approach chosen for site remediation has to take into consideration the extent of the contamination, the site location, and the desired end state or cleanup criteria. Removal of all contamination may not necessarily be the optimum or most practical solution. The objective of remediation is to reduce doses to exposed individuals or groups of individuals, to avert doses to such groups or individuals in the future, and to reduce or prevent the environmental impact [2]. Some remediation approaches are passive, while others are more active or may involve actual intervention. Remediation can also be carried out in-situ or ex-situ.

Remedial approaches generally fall into three main categories [3]:

- Removal of contamination to a more suitable location (a disposal or storage site for example).
- Containment of the contamination on-site.
- Dilution of the source of contamination.

There are essentially two end members to the remediation spectrum. The first revolves around the complete removal of all contaminated material. This approach can clearly be both expensive and time consuming and additionally relies on the availability of waste disposal systems to take the contaminated material. At the other end of the scale monitored natural attention can prove to be a viable strategy especially at sites where institutional control is likely to remain in force for many years after the cessation of site activities. With such an approach a site can take advantage of natural attenuation and dilution. The choice of approach and the timing therefore has to underpin the nature of the problem, the drivers for undertaking the remediation, and the agreed end state of the site. Sustainable and optimized solutions are often encouraged.

As highlighted in Section 13.1 there will also be many instances when remediation work will be required irrespective of a site's decommissioning activities. If we consider a nuclear site through its lifecycle there are many opportunities for activities or incidents to lead to the contamination of ground and groundwater. Common causes of contamination might include the following:

- Leaks from buildings and facilities.
- Leaks from surface storage compounds.
- Poorly performing waste disposal sites.
- Spills during the transportation of materials.
- Leaks from underground pipes.
- Aerial dispersion from stacks and incinerators.
- Past practices of allowing liquids to evaporate from hardstands.
- Cross-contamination of aquifers resulting from poorly designed boreholes.
- Dispersion of material during the decommissioning of facilities.

There are therefore many drivers to undertake remediation without or prior to decommissioning activities in order to reduce hazards to workers, the public, and the environment.

13.3 Selected case studies on environmental remediation projects

This section will provide some examples of where environmental remediation needed to be considered on nuclear licensed sites in conjunction with the planned decommissioning program. Each of the four examples demonstrate that the specific drivers for undertaking the remediation influenced how such activities linked into the site's decommissioning strategy, specifically the timing and adopted approach.

13.3.1 Hanford river corridor completion strategy

The Hanford site, located in Washington State, United States covers an area of 1518 sqkm (or km^2). Its original remit was to produce plutonium for national defense, and activities supporting this were carried out between 1943 and the late 1980s. In 1989 plutonium production ceased and the site focused more on waste management and environmental restoration.

The site cleanup consists of three major components: the river corridor, the central plateau, and the tank wastes, with each component presenting a complex and challenging undertaking involving multiple projects and requiring many years and billions of dollars to complete [4].

This case study will focus on the river corridor portion of the site, which is approximately 570 sqkm (or km^2) in area and includes the south shore of the Columbia River. This area of the site houses nine former plutonium production reactors, solid and liquid waste disposal sites, and support facilities. There are therefore a variety of contaminated land challenges. These challenges are not just radiological in nature (strontium, uranium) because hexavalent chromium resides in groundwater at levels over ten times above the drinking water standard. Cleanup of the river corridor has been one of the site's primary priorities since the 1990s and groundwater contamination continues to threaten the Columbia River. The overall challenges in this area relate to both decommissioning and remediation and it is recognized that the two activities need to be carefully coordinated.

The major challenges include the following:

- Remove, treat, and dispose of K Basin sludge.
- Place surplus production reactors into interim safe storage until final disposal.
- Prevent hexavalent chromium from impacting the Columbia River.
- Achieve strontium-90 river protection goal.
- Remediate the 300 area uranium plume.
- Demolish and close the 324 Building.
- Remediate 618-10/11 burial grounds.

The strategy for achieving the cleanup of the river corridor was set out in 2010 with the vision that the majority of the work would be complete by the end of 2015 (recognizing that some work elements would still be outstanding). Remedial approaches incorporating cleanup levels for both soil and groundwater were set prior to tackling the remediation. These cleanup levels cover the above/below-ground structures as well as the land itself, and they aim to provide adequate protection to human health and the environment in addition to allowing the land to be reused in line with the Hanford Comprehensive Land Use Plan (USDOE 1999) [5]. Fig. 13.2 shows cleanup work being carried out adjacent to the Columbia River and Fig. 13.3 depicts pump-and-treat remediation in the river corridor area.

It was deemed crucial that the cleanup approach included the many facilities and waste disposal areas. With the size of the area and the many decommissioning and remediation subprojects occurring in parallel, it was important to adopt a holistic and joined up approach. This would maximize worker safety and limit further ground and groundwater contamination.

Importantly, it was recognized that historical groundwater plumes (tritium, iodine, and nitrates) from the central plateau area of the site had not only reached the river corridor area, but also the Columbia River itself. Although contamination levels had decreased over time through natural attenuation, remedial activities focused on the plateau area will additionally and importantly restrict future plumes impacting on the river corridor area. A series of key performance measures (to have ideally been

Fig. 13.2 Cleanup work adjacent to the Columbia River.
From Mark Triplett, Pacific Northwest National Laboratory.

Fig. 13.3 Pump-and-treat remediation within the river corridor.
From Mark Triplett, Pacific Northwest National Laboratory.

achieved by 2015) were set and demonstrate the interaction between decommissioning and environmental remediation activities:

- Nine production reactors were to be demolished, cocooned, or dispositioned.
- Facilities to be demolished (522).
- High nuclear hazard facilities or waste sites to be remediated (20).
- Hot cells to be removed (20).
- Waste sites to be remediated (995).
- Waste and debris to be removed, treated, and disposed of (16.8 million tons).

This case study demonstrates that at a large complex site like Hanford it was crucial on the one hand to logically compartmentalize the site but also be aware of the effects each region might have on the other and therefore adopt a holistic remediation strategy. Close interaction between the various decommissioning and environmental remediation subprojects and activities was also imperative to maximize efficiency and funding, and facilitate a reduction of potential increased contamination.

13.3.2 ANL building 330 facility decontamination and demolition project

Building 330 on the Argonne National Laboratory (ANL) site was built in 1954 to accommodate the Chicago Pile 5 (CP-5) reactor. The site is located 27 miles southwest of downtown Chicago and is surrounded by both rural and populated areas. The role of this particular reactor was to produce neutrons and gamma rays for experiments as well as to serve as a training facility. Building 330 was taken out of service in 1979 and a year later all nuclear fuel and heavy water was transported to the Savannah River site in South Carolina. The facility then spent the next 12 years in a dry lay-up condition prior to a period of decontamination and dismantling between the years 1992–2000 [6]. The following objectives were set out for the decontamination and demolition program:

- Remove all hazardous and asbestos-containing materials.
- Remove all interior mechanical, electrical, architectural systems and components and physical structures.
- Package and transport waste materials to approved disposal facilities.
- Conduct a final status survey.
- Backfill the excavated area up to the surrounding grade level.
- Install an impermeable asphalt barrier cap.
- Reseed the site with groundcover plantings.
- Release the site for use under Argonne's continued scientific research and development mission.

This phase of the work commenced in 2009, but following the removal of the majority of building debris and excavation of foundations, radiological monitoring detected elevated gamma levels beneath where the E wing had resided. A further characterization was therefore undertaken in 2011 that identified some discrete areas of Cs^{137} within soil samples. Localized soil removal was undertaken in order to remove these areas of contamination.

The final status survey for the Building 330 footprint area was undertaken in May 2011 and was designed and conducted in accordance with Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) guidance. The survey comprised surface gamma scans and the collection and analysis of soil samples. Some small areas of contaminated soil in excess of the Cs^{137} criterion remained, but the contractor concluded that the results demonstrated that average concentrations appeared to satisfy the previously established project criteria. However, because there was no established elevated measurement comparison (EMC) for use when derived concentration guideline levels (DCGLs) were exceeded, the site administrators felt there was no MARSSIM technical basis to support the conclusion reached. The in-house ANL team (based on the site history and the results of previous investigations) subsequently developed a list of likely contaminants (Tc^{99}, Am^{241}, Ba^{133}, c^{14}, Cs^{137}, Sr^{90}, Pu^{238}, and $Pu^{239}/^{240}$) and DCGLs for potential reuse of the site. When the $DCGL_{EMC}$ was applied to the sample results (thus comparing the elevated readings to the release criteria) it was deemed that the release criteria had been met.

An independent verification survey was also undertaken but those responsible for this survey did not have sight of the original contractor report during that time. The independent survey concluded that three of nine survey units did not meet the established release limit for Cs.^{137} It was therefore recommended that this material should not be reused as backfill material. They additionally recommended that further remediation should be undertaken or the material could only be released if agreed restrictions to its use were in place. Figs. 13.4 and 13.5 **s**how site characterization and soil removal around B330.

Fig. 13.4 Site characterization around B330 at ANL's Chicago site.
From Larry Moos, Argonne National Laboratory.

Fig. 13.5 Site characterization and soil removal around B330 at ANL's Chicago site.
From Larry Moos, Argonne National Laboratory.

Once ANL and USDOE were satisfied with the confirmatory radiological surveys, approval was given to backfill the excavated area. This was undertaken by placing clean borrowed soil into the excavation, capping with an asphalt cap, and then covering the disturbed areas with topsoil and seeding them. The completion of the project allowed USDOE to issue an unrestricted use designation for the site, and the establishment of

DCGL values for the primary contaminant of concern allowed the area to be reused in line with ANL's mission of delivering innovative research and technology.

In terms of lessons learned, if an approach had been adopted that minimized or eliminated the spread of contaminated materials to other parts of the excavation, this might have reduced the requirement for further remediation and reduced delays and expense to the contractors during the final status survey. The contractors' final status survey report could have been prepared, thoroughly reviewed, and provided to the independent varication survey team prior to their arrival on-site. This would have facilitated any issues being resolved before the independent verification was undertaken. Because the soil residing below the building was only assessed and remediated many years after the demolition work, different contractors were utilized. This in turn led to additional costs in relation to many of the project components like mobilization, project management, project controls, and field inspectors.

13.3.3 The Windscale trenches

The Sellafield site is located on the northwest coast of England in West Cumbria. The industrial history of the site is both varied and complex, with the initial activities commencing in 1941. It was originally developed as a Royal Ordnance Factory for the production of trinitrotoluene (TNT) but following cessation of this activity at the end of World War Two the site was cleared (1946). The following year the government acquired the site in order for it to be the location for Britain's plutonium production plant. In the early 1950s, the world's first civil nuclear power generation reactors (Calder Hall) were constructed and the site has been developed and expanded ever since. With the exception of a prototype reactor built in the 1960s, this further expansion was primarily in support of the reprocessing of spent nuclear fuel and the temporary storage of solid and liquid reprocessing wastes prior to their vitrification, encapsulation, and more permanent storage. Fig. 13.6 shows a historical photograph of the trenches. Please note the proximity to other facilities within this compact area of the site.

Fig. 13.6 Historical photo of the Windscale trenches at Sellafield. Photo courtesy of Sellafield Ltd.

For many years Sellafield has undergone extensive phases of decommissioning. This decommissioning work continues today and takes place alongside the site's existing operations. Owned by the Nuclear Decommissioning Authority (NDA) the Sellafield site's legacy ponds and silos remain their greatest decommissioning challenge, and therefore priority, across their entire estate. The NDA's overall strategy remains to decommission all their sites as soon as reasonably practicable, taking account of lifecycle risks to people and the environment and other relevant factors [7]. Although their preference is for continuous decommissioning it is recognized that on some occasions there may be clear benefits to be had from deferring this kind of work. Such an approach may, for example, allow a site operator to take benefit from radioactive decay or natural attenuation when considering future risk to human health and the environment.

The Windscale Trenches within the central part of the site (separation area) were the primary on-site disposal facility for solid radioactive wastes in the 1950s. These unlined trenches are thought to contain wastes that would today be categorized as low-level waste (LLW). Much of the original radioactive inventory is thought to be tritium associated with furnace liners and filters disposed following the 1957 Windscale fire. It is likely, however, that other fission products and actinides will be present in addition to a range of nonradiological components. There is also a reasonable possibility that small amounts of short-lived intermediate-level waste (ILW) may have been disposed.

Around 40%–50% of the area associated with the trenches was partially reprofiled (to enhance surface drainage) and capped with tarmac. The remaining uncapped areas were either vegetated or covered with hard-core or tarmac, but not really with any specific regard for protection of the trench wastes.

Tritium contamination is observed offsite in springs on the nearby beach in a direction that is broadly consistent with the direction of groundwater flow to the southwest of the facility. Although the tritium is likely to be associated with a number of sources in the separation area it is believed that releases from the trenches are likely to contribute to the observed concentrations. Modeling studies suggest that the offsite impacts of any future releases from the trenches will continue to be negligible. However, the conceptual understanding that underpins the modeling studies suggests it is likely that there might be a continual release from the trenches to groundwater if some form of intervention was not considered. This is due to the flow of meteoric water through the trenches and the associated release of radionuclides (including less mobile fission products and actinides) and other contaminants.

From the site operators' perspective there are clear drivers that revolve around demonstrating optimization in how the trenches are managed. Such drivers include liability management and the development of robust management plans. Nuclear regulatory drivers are also clearly crucial (Nuclear Site License Conditions 32 and 34), as are environmental regulatory requirements (i.e., those relating to the Groundwater Directive). So even though the offsite risks are considered to be low, the potential for uncontrolled release of contaminants from the trenches to the unsaturated zone and underlying groundwater requires the identification of an appropriate, proportionate management strategy to control any migration.

The site operators therefore decided to hold a stakeholder workshop in order to consider potential management options for the trenches [8]. The workshop's main aim was to reach a consensus on a preferred interim management option. An interim option was sought because the focus of the assessment was on the management of the trenches over the short- to medium-term, in other words, the next few decades, rather than an option that met a potential but yet unknown final end state.

There is still uncertainty regarding the finer details of the final end state for the Sellafield site, but the current assumption is that this might be achieved around 2120. There is therefore not a strong driver to achieve a final end state for the trenches today, although it was recognized that the interim management approach should not unreasonably foreclose potential longer term options. The key requirement was therefore to identify an interim management approach, demonstrating that it met present-day site licensee and regulatory requirements.

It was agreed that the assessment process would be systematic and assess key differentiators between options against identified criteria of interest. A largely flexible and qualitative assessment approach was undertaken with the aim of assisting the assessment of variants or combinations of options that may together represent the best available technology (BAT) [8].

Six management strategy options were initially proposed:

- No change to current arrangements.
- Improved near-surface management (enhanced or complete cap).
- In situ stabilization.
- Ex situ vitrification.
- Groundwater pumping or treatment, or groundwater barriers.
- Partial or complete excavation followed by waste treatment and storage and/or disposal.

A qualitative assessment of the strengths and weaknesses of each of these options against a range of high-level criteria was then undertaken. The analysis had two main aims. The first aim was to identify which options offered a net benefit in terms of protection of human health and the environment; the second aim was to help facilitate gaining a consensus view on which of these approaches represented the proportionate response to achieving these protection requirements. Based upon the analysis, three of the six options were taken forward and a further and more detailed assessment was then undertaken against a range of attributes:

- No change to current arrangements.
- Improved near-surface management (enhanced or complete cap).
- Partial or complete excavation followed by waste treatment and storage and/or disposal.

Following this detailed assessment a preferred option was eventually identified;

“The installation of a reprofiled and drained tarmac cap above those areas of the Trenches not currently capped, thereby providing an integrated single cap over the whole Trench area” [8].

As highlighted above, although the decommissioning of legacy facilities at Sellafield remains the NDA’s (and undoubtedly the regulators) highest priority, the Sellafield site has not ignored other regulatory expectations revolving around the assessment and management of contaminated land and groundwater. The BAT assessment process applied to the Windscale trenches provide a good example of where the site operators have been proactive in choosing an optimized and sustainable solution for at least the short- to medium-term that meets stakeholder expectations, fits into the current decommissioning strategies across the site, and considers the longer term goal of achieving a final site end state.

13.3.4 Dounreay Environmental Restoration Programme Plan (ERPP)

The Dounreay site is located on the north coast of Scotland, United Kingdom and is operated by Dounreay Site Restoration Ltd (DSRL), a wholly-owned subsidiary of the Cavendish Dounreay Partnership Ltd. The site was chosen to house the Dounreay Fast Reactor (DFR), which achieved criticality in 1959 [9]. A test reactor (the Dounreay Materials Test Reactor) was constructed and actually achieved criticality in 1958. The fast reactor chemical separation plant was also completed in 1959 in order to reprocess spent fuel. As the site expanded in size and in its activities, numerous supporting laboratories and service facilities were also constructed around this time. In 1974, a prototype fast reactor became operational supplying electricity to the grid the following year. From 1994 onwards, the majority of site programs were aimed toward the reprocessing and manufacture of fuel, but over the last decade site activities have been more focused on decommissioning and cleanup.

This relatively small but complex site therefore accommodated a range of reactors, waste disposal facilities, waste treatment and storage facilities, fuel fabrication plants, fuel pond storage facilities, and a variety of research and support laboratories. The Dounreay Site Closure Process (facilitated by the Environmental Restoration Programme Plan) is well underway and the site intends to declare both an interim and final end state. This program is aimed to take the site to its interim end state. Fig. 13.7 shows the Dounreay site.

Fig 13.7 The Dounreay site.
Photo courtesy of the DSRL and NDA.

The ERPP commences during the decommissioning of the many facilities and revolves around a series of activities, including the following [10]:

- Characterization of land, floor slabs, sub structures, services, and groundwater.
- Demolition of structures above the floor slab level.
- Remediation of land, floor slab, sub structures, services, and groundwater that do not satisfy the interim end state objectives.
- Restoration and landscaping of the site.

Site closure will be implemented on a zone-by-zone basis with each zone being grouped and cleared in three phases. Such an approach allows work to be undertaken incrementally and in a manner that addresses the least contaminated areas first, thus allowing the process and lessons learnt to be adapted where necessary. In order to focus remediation activities a series of cleanup levels for the key contaminants of concern were established that would facilitate achieving unrestricted reuse at the final end point (Please note, both the terms "final end state" and "final end point" are used by DSRL).

DSRL has rightly stated that characterization is the key to decision making; in other words robust and accurate characterization lays the foundation for the decisions to be made and provides confidence and justifiability in these decisions. Four distinct stages are set out for the closure lifecycle: decommissioning, demolition, remediation, and restoration.

Because some of the selected zones might be too complex to be addressed individually DRSL has opted (when deemed beneficial) to split a zone into distinct study areas. These study areas may be based upon the configuration and layout of facilities, infrastructure, or ground contamination. As the four closure stages progress it is crucial to not look at each in isolation. For example, although during the decommissioning phase the remediation of the floor slabs and subsurface infrastructure resides with the decommissioning projects, such work may be deferred until remediation of the adjacent land has been undertaken. The remediation phase itself is aimed at removing any remaining contaminants from the ground, subsurface structures, and infrastructure once the demolition phase is complete such that the average levels remaining meet the interim end state criteria.

This case study shows that in this kind of program there are many integral links between the different phases of work and subprojects during the four closure stages set out. Issues like timing, the generation of wastes, accessibility, and validation of objectives all need to be factored in. The two technical areas of decommissioning and environmental remediation cannot be viewed in isolation. Such relationships are recognized and mapped out in Fig. 13.6 of [10]. Some of these activities will undoubtedly be iterative in nature because the validation process determines whether the work has been successful or not in reducing contamination to acceptable levels.

At the time of writing this chapter it is believed that the site owners (the NDA) and DSRL might be revisiting the proposed interim and final site end states and how these might be achieved.

13.4 Lessons learned

The key lessons to be learned revolve around the fact that although decommissioning and environmental remediation are clearly distinct disciplines in terms of their precise objective, they will often go hand in hand. It is therefore important to consider if and when such activities can be integrated and/or sensibly timed in order to ensure that sites can, where applicable, adopt a holistic and sustainable approach to meet their desired end state.

The decommissioning and remediation work for the B330 facility on the Argonne site provides an example of how a greater integration between the two activities will undoubtedly save some time and expenditure and minimize the requirement for continued assessment and validation surveys on projects. Establishing clear and agreed upon cleanup criteria at the outset of a project is crucial.

At the United Kingdom's Sellafield site an optimized and sustainable approach to managing the legacy waste trenches was realized through adopting a transparent decision making process in the presence of a range of stakeholders. Even though the final end state for this site will not be realized until around 2120, it is necessary to have clear objectives of how health and safety, security, and environmental protection are to be maintained through operation and until the closure period. At this site sustainable remediation approaches are being adopted that consider the many complex decommissioning activities, thus allowing a holistic approach to be taken.

The Hanford site in the United States is probably the largest and most complex nuclear site in the world. With the large variety of different projects and contractors working on parallel missions it was important to compartmentalize the site yet ensure that a high-level of communication and coordination takes place. This case study demonstrates once more that close interaction between the various decommissioning and environmental remediation subprojects and activities was imperative in maximizing efficiency and funding, and facilitating a reduction of potential increased contamination. Both decommissioning and remediation activities have taken place and continue to take place in a coordinated manner in order to meet stakeholder expectations, as well as site end state and cleanup objectives.

The United Kingdom's Dounreay site has set out its intentions on how to meet an interim and final end state (although the process is likely to be revisited). The site operators have carefully mapped out the relationships between different work programs and technical disciplines as they move towards meeting the interim end state. The timing of decommissioning and remediation has clearly been considered in order to ensure accessibility to below-ground contamination and to accurately predict waste volumes and inventories. The fact that the process for determining the interim and final site end state is being revisited perhaps demonstrates that such work is never straightforward, new information or thought processes may come to light, options can never be ruled out, that overall an iterative approach needs to be kept in mind.

13.5 Future trends

Many nuclear site operators are either planning decommissioning or undertaking active decommissioning. While it is recognized that environmental remediation may not always be required to form part of a decommissioning strategy it is nevertheless logical to adopt a formalized process within the decommissioning plan that allows such a determination to be made (or not) so that where necessary it can be factored in. Such a formalized process would reduce uncertainty in waste streams, limit the chances of further work being required at a later date and provide enhanced confidence to regulators and other stakeholders. Many sites do consider both technical disciplines when setting out their strategy for meeting a desired end state, but perhaps the potential for remediation could be captured in a more formalized manner.

It is crucial that the setting of site end states, with its supporting decommissioning and remediation activities, is viewed as an iterative process. If after site closure the land maintains certain restrictions (i.e., it has not been cleared for unrestricted reuse) for its further use there will still be a requirement to have some form of institutional control. This may relate to site management, groundwater monitoring, and the custodial duties of finances. A big difference between decommissioning and remediation is that above-ground structures can be seen and therefore once removed it is easier to validate the overall success criteria. This is not necessarily the case with below-ground contamination, especially if the geology and hydrogeology are complex. The “goal posts” may move as new information comes to light, legislation may be refined or stakeholder expectations may change, even after a site has been decommissioned and remediated. Linking the two subjects can only assist in getting it right first time.

International organizations like the International Atomic Energy Agency (IAEA) are encouraging a greater consideration of lifecycle thinking when planning the decommissioning and environmental remediation of sites, and they promote a greater interconnection of the two areas [11].

13.6 Summary and conclusions

Decommissioning and environmental remediation are two technical activities that, depending on the circumstances, may be undertaken independently or in conjunction with the other. The timing of environmental remediation at a site will invariably be directed by the drivers that necessitate it. In many instances a site will require both activities as it moves from operation through closure to its agreed end state. These activities need to factor in each other; otherwise there is the potential for communication problems, escalating timescales and costs, work having to be redone, loss of regulatory confidence, and incorrect choices for applied technologies.

Site cleanup involves dealing with above- and below-ground structures, contaminated land, and impacted groundwater. Integrating these two disciplines that support the delivery of cleanup is therefore imperative. The four case studies, although brief, show that coordinating these activities will often result in an increase of regulatory and stakeholder confidence and the likelihood of project success, while the reverse often leads to some level of project failure.

Notwithstanding the conclusions above it should also be recognized that there will be some occasions when environmental remediation will be required at a nuclear site without the occurrence of decommissioning activities.

13.7 Sources of further information and acknowledgements

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Dawn Wellman, Pacific Northwest National Laboratory

Further information on the sites highlighted within this chapter can be found at the following websites.

http://www.hanford.gov/
http://www.anl.gov/
http://www.sellafieldsites.com/
http://www.dounreay.com/

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