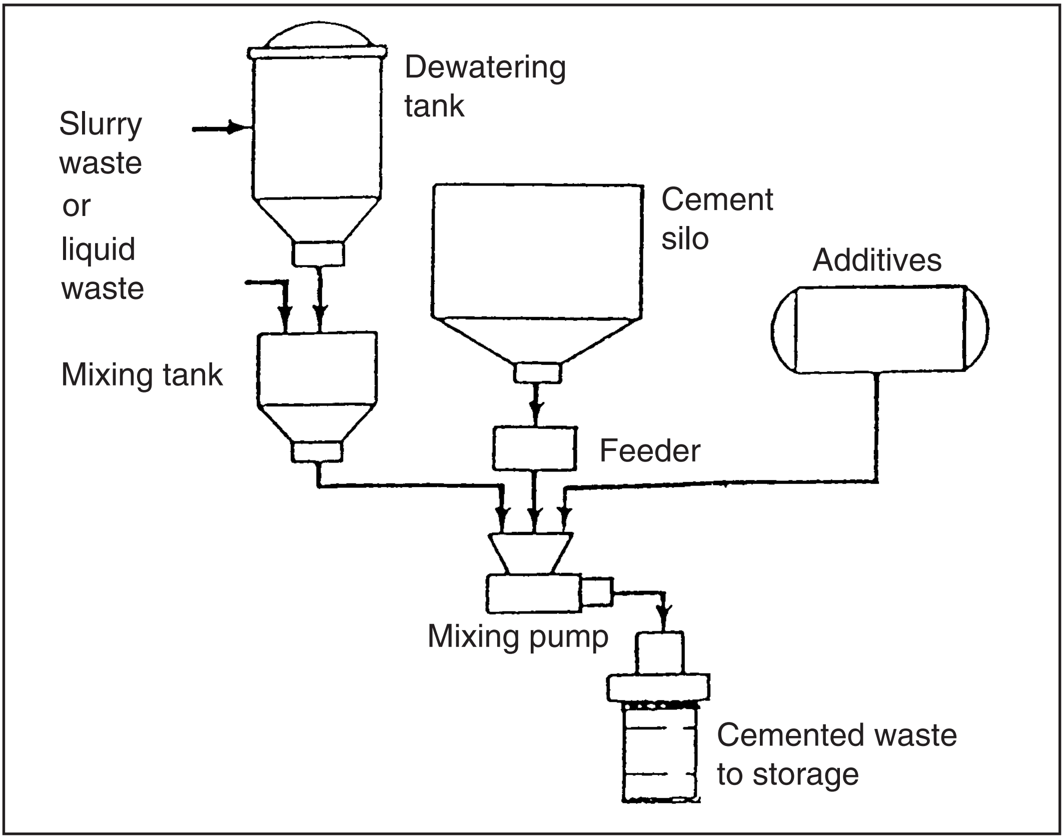

TECHNICAL REPORTS SERIES No. **402**

Handling and Processing of Radioactive Waste from Nuclear Applications

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2001

HANDLING AND PROCESSING OF RADIOACTIVE WASTE FROM NUCLEAR APPLICATIONS

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

Printed by the IAEA in Austria
October 2001
STI/DOC/010/402

TECHNICAL REPORTS SERIES No. 402

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2001

VIC Library Cataloguing in Publication Data

Handling and processing of radioactive waste from nuclear applications. —
Vienna : International Atomic Energy Agency, 2001.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; no. 402)
STI/DOC/010/402
ISBN 92–0–100801–5
Includes bibliographical references.

1. Radioactive waste disposal. I. International Atomic Energy Agency. II. Series : Technical reports series (International Atomic Energy Agency) ; 402.

VICL 01–00260

FOREWORD

A wide variety of technical options is available for processing radioactive waste generated in the nuclear power industry and during various nuclear applications. The selection of an appropriate technology for waste processing depends mainly on the characteristics of the waste, the scale of waste production and the requirements for the final waste form. Since wastes generated from nuclear applications are very different in terms of their volumes and characteristics from those generated in the nuclear power industry, in many cases they require different approaches to the whole system of treatment, conditioning and storage.

Recognizing the increasing importance of the subject for its Member States, the IAEA has prepared two reports to assist waste managers and waste operators in developing Member States. IAEA-TECDOC-1041, Management of Small Quantities of Radioactive Waste, was published in 1998 to provide practical guidance and to assist managers dealing with small amounts of radioactive waste in developing Member States. The document provides information on the different components of the waste management process as a whole and briefly lists the basic technologies used.

This report has been prepared to provide detailed information on the handling, processing and storage techniques most widely used and recommended for waste from non-fuel cycle activities mainly in developing Member States. This information is intended to assist operators of waste processing and storage facilities, with the emphasis on the most simple, affordable and reliable techniques available in non-nuclear power generating countries. The report summarizes the information previously collected and described in a number of technical documents (IAEA TECDOCs) published from 1992 to 1995, which were designed mainly for Member States without nuclear power or fuel cycle activities but that have radioactive waste generated during the application of nuclear technologies and radioisotopes in industry, medicine, research and education. This report is intended to review, analyse and summarize this information based on up to date experience and existing practice.

The initial report was prepared by the Secretariat with the assistance of consultants from Austria, Canada, Pakistan, the United Kingdom and the United States of America. The draft was then revised by a series of consultants meetings based on comments and additional information collected. The IAEA would like to express its thanks to all those who took part in the preparation of the report, particularly P. Colombo (USA) and M. Garamszeghy (Canada) who were involved in the preparation of the final version of this report. The IAEA officer responsible for this report was V. Efremenkov from the Waste Technology Section of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Radioactive materials are extensively used in industrial and research activities into medical, agricultural and environmental applications, and in various other areas. During the production and use of these materials, radioactive waste will inevitably arise; this must be managed with particular care owing to its inherent radiological, biological, chemical and physical hazards. Producers and users of radioactive materials must be sure that a waste management strategy exists prior to the start of waste generation. A well developed waste management strategy should consider the entire sequence of waste management operations, from the waste's production until its final disposal, including the various regulatory, sociopolitical and economic issues.

The overall goal of radioactive waste management is to deal with radioactive waste in a manner that protects both human health and the environment now and in the future, without imposing an undue burden on future generations. Waste management includes the handling, pretreatment, treatment, conditioning, storage, transportation and disposal of conditioned radioactive waste, as well as the release and discharge of decontaminated materials. The identified goal of radioactive waste management can be met with reasonable cost and resource use by implementing a carefully planned waste management strategy using appropriate technologies. For example, an important technique for the management of low level radioactive waste contaminated with short lived radionuclides is to store the waste under well controlled conditions until the radioactivity has decayed to a level such that the waste can be categorized as non-radioactive, or meets established exemption or clearance limits. Waste containing long lived radionuclides must be treated, conditioned, stored and disposed of at a repository specifically designed for this purpose. Ample storage capacity is needed for the decay of short lived radionuclides and for storing long lived waste prior to, and after, the treatment and conditioning steps.

Decay is the only natural way of reducing radioactivity (the process of transmutation of some long lived radionuclides is not considered viable at this time). Since radionuclides have decay rates ranging from days to thousands of years, proper segregation of wastes depending on their half-lives, and separate treatment and conditioning of these wastes, is an important factor in the overall scheme of radioactive waste management.

1.2. OBJECTIVE AND SCOPE

The main objective of this report is to provide technical information and reference material on the different steps and components of radioactive waste management for staff in establishments that use radionuclides and in research centres in Member States. It provides technical information on the safe handling, treatment, conditioning and storage of waste arising from the various activities associated with the production and application of radioisotopes in medical, industrial, educational and research facilities. The appropriate technical information can be used in the development of waste management programmes for meeting the particular needs and existing capabilities of countries with limited nuclear activities. Readers interested in more detail may consult the reference list at the end of this report, which gives details of additional waste management literature. The technical information cited in this report consists mainly of processes that are commercialized or readily available, and can easily be applied as they are or modified to solve specific waste management requirements.

While this report is intended primarily for developing Member States that produce limited amounts of radioactive waste, it also reflects the practices applied in countries with larger programmes of nuclear applications. This report could, therefore, be useful for any establishment dealing with the production and application of radioisotopes, and consequently with the waste associated with such activities. Waste produced at commercial nuclear power plants and established fuel cycle facilities is not considered in this report, although many of the techniques described are applicable to this type of waste.

This report covers the sources and characteristics of waste and approaches to waste classification, and describes the particular processing steps from pretreatment until storage of conditioned packages. Disposal options are not considered. Management of spent sealed radioactive sources is not specifically considered in this report since they are discussed in other publications.

It should be noted that this report provides information on the general approaches and particular technologies applied in the processing of waste from the most widely used nuclear applications. However, waste management concepts and practices can vary considerably from one country to another, depending on local conditions and established requirements. Selection of a particular option or specific technology for waste treatment and conditioning may be site specific, and will depend on many factors.

1.3. STRUCTURE

Section 2 outlines the scale of waste production in different countries based on their respective nuclear activities and associated production of radioactive waste. The sources, volumes, types and activity levels of waste generated by non-nuclear fuel cycle activities in these countries are estimated and summarized.

Section 3 provides information on the existing approaches to waste classification schemes relating to radiation protection, treatment, conditioning and storage requirements, exemption limits and clearance levels, and the availability of disposal options.

Section 4 presents the basic principles and requirements for planning and establishing a systematic approach for the development of a national waste management policy and a national waste management programme. Important technological steps to be considered for the management of radioactive waste from generation to disposal are described.

Section 5 addresses the storage of unconditioned waste at various radioisotope production facilities, research centres and user establishments. It includes design features for an interim storage facility and specifies techniques and requirements for storing organic, biological and medical radioactive waste.

Section 6 provides a description of the processes that are most commonly used for treating liquid radioactive waste. It begins with general considerations and a summary of the methods applied, and proceeds to more specific processes for removing problem radionuclides (e.g. strontium and caesium) from aqueous waste streams.

Section 7 examines processes for treating radioactive liquid organic wastes such as oils, scintillation fluids and miscellaneous solvents.

Section 8 deals with treating solid radioactive waste. It includes processes that are conventionally used, and those that are used for waste that requires special treatment considerations, such as solid and wet solid medical and biological radioactive waste.

Section 9 identifies and reviews a wide range of contemporary matrix materials and processes for conditioning liquid and solid waste. It begins with a description of the physical and chemical properties of the most commonly used matrix materials (e.g. cement, bitumen and polymers), describes their chemical compatibility with selected waste and waste constituents and concludes with an account of compatible processing systems and equipment.

Section 10 describes cementation processes for conditioning radioactive waste (e.g. ion exchange resins, precipitation sludges and evaporator concentrates) that may require prolonged storage. It includes waste feed compositions based on the operational experience of various countries and the sequential steps of the conditioning process. A comprehensive review of conditioning processes for animal carcasses, organic liquids and non-combustible, non-compactible waste is also presented.

Section 11 reviews the criteria for selecting containers used for packaging conditioned waste, and summarizes the properties and characteristics of the most commonly used containers.

Section 12 describes the requirements for the interim storage of radioactive waste packages. The design features for an acceptable storage facility, including waste package handling, operating procedures and safety related aspects, are discussed.

Section 13 considers the quality assurance related issues important for the development of a comprehensive waste management programme. The general qualitative acceptance concept for a waste repository is given, along with guidelines regarding system requirements, record keeping and auditing.

Section 14 discusses the conclusions derived in this report from the operational experience of Member States in waste management activities, including the pretreatment, treatment, conditioning and storage of radioactive waste prior to disposal.

2. WASTE ARISINGS

Radioactive waste is generated in all stages of nuclear research reactor operations and in operations involving the production of radioisotopes and their application in medicine, industry and research. The types and volumes of waste produced depend upon the particular operation being conducted, and can vary extensively in radiochemical, chemical and physical content.

The principal types of waste generated during the production and application of radioisotopes are listed in Table I [1].

2.1. SOURCES OF WASTE

2.1.1. Nuclear research centres

In small nuclear research centres radioisotopes are produced in research reactors or in particle accelerators. The desired radioisotopes are subsequently extracted or processed in nearby hot cells or laboratories. Most of the radioactive waste generated during these operations contains a mixture of long and short lived radioisotopes and should be managed to provide for decay, dilution and subsequent discharge, or for conditioning into a form suitable for long term storage and/or disposal. Waste containing long lived fission products and/or transuranic radionuclides is not usually generated in the laboratories of small nuclear research centres in developing countries. Only a small part of radioactive waste from these centres will be contaminated with long lived radioisotopes, for example ^{14}C and ^{3}H from limited laboratory experiments or uranium and thorium from processing investigations in laboratory and pilot plant scale operations.

TABLE I. PRINCIPAL TYPES OF RADIOACTIVE WASTE GENERATED DURING THE PRODUCTION AND APPLICATION OF RADIOISOTOPES

Waste category	Waste type
Liquids, aqueous	Laboratory effluents Hot cell (isotope production) effluents Fuel storage pool (research reactor) purges Decontamination effluents Sump and rinsing waters Mining and milling raffinates with uranium and thorium from laboratory and pilot plant scale extraction
Liquids, organic	Oil from pumps, etc. Scintillation liquids Extraction solvents (tributylphosphate (TBP)/kerosene, amine, etc.)
Solids, compactible	Tissues, swabs, paper, cardboard, plastics (polyvinylchloride, polyethylene), rubber gloves, protective clothes, filters and glassware
Solids, non-compactible	Metallic scrap, brickwork, sealed sources, radium needles, ion exchange resins, animal carcasses and excreta

2.1.2. Hospitals

The application of radioactive materials in medical diagnosis and therapy is extremely important and continuously expanding. In many instances alternative methods are not available. The main areas of applications are in radioimmunoassays, radiopharmaceuticals, diagnostic procedures, radiotherapy and research. These represent the use not only of small quantities of unsealed sources and liquid solutions, but also of highly concentrated sealed sources housed in shielded assemblies. A variety of radionuclides used in medical applications, in both unsealed and sealed forms, are listed in Table II and Table III, respectively [2].

Most of the radioisotopes used in hospitals for medical diagnostic procedures and treatments are very short lived, and in most cases the only treatment performed on the waste is storage for decay before further treatment to eliminate biological hazards and/or release to the environment.

TABLE II. PRINCIPAL RADIONUCLIDES USED IN MEDICINE AND BIOLOGICAL RESEARCH

Radio-nuclide	Half-life	Principle application	Typical quantity per application	Waste characteristics
^{3}H	12.3 a	Radiolabelling Biological research Organic synthesis	Up to 50 GBq	Solvents, solid, liquid
^{14}C	5730 a	Medical Biological research Radiolabelling	Less than 1 MBq Up to 50 GBq Up to 50 GBq	(Exhaled CO_2), solid, liquid, solvents
^{18}F	1.8 h	Positron emission tomography	Up to 500 MBq	Solid, liquid
^{24}Na	15.0 h	Biological research	Up to 5 GBq	Solid, liquid
^{32}P	14.3 d	Clinical therapy	Up to 200 MBq	Solid, liquid
^{33}P	25.4 d	Biological research	Up to 50 MBq	
^{35}S	87.4 d	Medical and biological research	Up to 5 GBq	Solid, liquid
^{36}Cl	3.01×10^{5} a	Biological research	Up to 5 MBq	Gaseous, solid, liquid
^{45}Ca	163 d	Biological research	Up to 100 MBq	Mainly solid, some liquid
^{46}Sc	83.8 d	Medical and biological research	Up to 500 MBq	Solid, liquid
^{51}Cr	27.7 d	Clinical measurements Biological research	Up to 5 MBq Up to 100 MBq	Solid Mainly liquid
^{57}Co	271.7 d	Clinical measurements	Up to 50 MBq	Solid, liquid
^{58}Co	70.8 d	Biological research	—	
^{59}Fe	44.5 d	Clinical measurements Biological research	Up to 50 MBq	Solid, liquid
^{67}Ga	3.3 d	Clinical measurements	Up to 200 GBq	Solid, liquid
^{75}Se	119.78 d	Clinical measurements	Up to 10 MBq	Solid, liquid
$^{81}Kr^{m}$	13.3 s	Lung ventilation studies	Up to 6 GBq	Gaseous
^{85}Sr	64.8 d	Biological research	UP to 50 MBq	Solid, liquid
^{86}Rb	18.7 d	Medical and biological research	Up to 50 MBq	Solid, liquid

TABLE II. (cont.)

Radio-nuclide	Half-life	Principle application	Typical quantity per application	Waste characteristics
^{82}Rb^{m}	6.2 h	Clinical measurement	—	Solid, liquid
^{89}Sr	50.5 d	Clinical therapy	Up to 300 MBq	Solid, liquid
^{90}Y	2.7 d	Clinical therapy Medical and biological research	Up to 300 MBq	Solid, liquid
^{95}Nb	35.0 d	Medical and biological research	Up to 50 MBq	Solid, liquid
^{99}Tc^{m}	6.0 h	Clinical measurements Biological research Nuclide generators	Up to 100 GBq	Solid, liquid
^{111}In	2.8 d	Clinical measurements Biological research	Up to 50 MBq	Solid, liquid
^{123}I	13.2 h	Medical and biological research	Up to 500 MBq	Solid, liquid, occasionally vapour
^{125}I	60.1 d	Clinical measurements	Up to 11.1 Bq	
^{131}I	8.0 d	Clinical therapy		
^{113}Sn	155.0 d	Medical and biological research	Up to 50 GBq	Solid, liquid
^{133}Xe	5.3 d	Clinical measurements	Up to 400 GBq	Gaseous, solid
^{153}Sm	1.9 d	Clinical therapy	Up to 8 GBq	Solid, liquid
^{169}Er	9.3 d	Clinical therapy	Up to 500 MBq	Solid, liquid
^{198}Au	2.7 d	Clinical measurements	Up to 500 MBq	Solid, liquid
^{201}Tl	3.0 d	Clinical measurements	Up to 200 MBq	Solid, liquid
^{203}Hg	46.6 d	Biological research	Up to 5 MBq	Solid, liquid

2.1.3. Industry

Certain industrial establishments use particular forms of radioactive materials and techniques, such as radioactive tracers, sealed sources and luminous displays, and specialized devices for non-destructive testing, quality control, evaluation of plant performance and the development of products. The quantities of radioactive materials used depend largely on the level of the development of technology in that country. Several of these applications are shown in Table IV.

TABLE III. SEALED SOURCES USED IN MEDICINE AND MEDICAL RESEARCH

Application	Radionuclide	Half-life	Source activity	Comments
Bone densitometry	^{241}Am	433.0 a	1–10 GBq	Mobile units
	^{153}Gd	244.0 d	1–40 GBq	
	^{125}I	60.1 d	1–10 GBq	
Manual brachytherapy	^{198}Au	2.7 d	50–500 MBq	Small portable sources
	^{137}Cs	30.0 a	30–300 MBq	
	^{226}Ra[a]	1600 a	50–500 MBq	
	^{60}Co	5.3 a	50–1500 MBq	
	^{90}Sr	29.1 a	50–1500 MBq	
	^{103}Pd	17.0 a	50–1500 MBq	
	^{125}I	60.1 d	200–1500 MBq	
	^{192}Ir	74.0 d	5–100 MBq	
	^{106}Ru	1.01 a	10–20 MBq	
	^{90}Y	2.7 d	50–500 MBq	
Vascular brachytherapy	^{32}P	14.3 d	200 MBq	Catheterization
	^{89}Sr	50.5 d	150 MBq	
	^{192}Ir	74 d	0.1–1 TBq	
Remote after-loading brachytherapy	^{137}Cs	30.0 a	0.03–10 MBq	Mobile units
	^{192}Ir	74.0 d	0.1–200 TBq	
Teletherapy	^{60}Co	5.3 a	50–1000 TBq	Fixed installations
	^{137}Cs	30.0 a	500 TBq	
Whole blood irradiation	^{137}Cs	30.0 a	2–100 TBq	Fixed installations
	^{60}Co	5.3 a	50–1000 TBq	
Research	^{60}Co	5.3 a	Up to 750 TBq	Fixed installations
	^{137}Cs	30.0 a	Up to 13 TBq	
Calibration sources, anatomical markers, sources as standards in instruments	^{63}Ni	96 a	<4 MBq	Fixed installations, in instruments or mobile sources
	^{137}Cs	30.0 a	<4 MBq	
	^{57}Co	271.7 d	Up to 400 MBq	
	^{226}Ra[a]	1.6×10^3 d	<10 MBq	
	^{147}Pm	2.62 a	<4 MBq	
	^{36}Cl	3.01×10^5 a	<4 MBq	
	^{129}I	1.57×10^7 a	<4 MBq	
Gamma radiosurgery knives	^{60}Co	5.3 a	Up to 220 TBq	Skull cap

[a] Radium sources are not generally used for therapeutical treatments, but exist in many hospitals as spent sources.

TABLE IV. VARIOUS INDUSTRIAL APPLICATIONS OF RADIONUCLIDES

Radio-nuclide	Form of application		
	Sealed sources	Tracers	Others
^{3}H	Foil thickness measurements	Water movement	Luminous articles and electronic valves
^{32}P	Foil thickness measurements	Agriculture	
^{41}Ar		Leak testing and gas movement	
^{46}Sc		Silt movement	
^{57}Co	Check sources		Occasionally in electronic valves
^{60}Co	Industry, radiotherapy, clinical therapy, sterilization		
^{63}Ni	Foil thickness measurements		
^{82}Br		Water movement and leak testing	
^{85}Kr	Gauging		Occasionally in electronic valves
^{90}Sr	Thickness gauges, eye applicators		
^{137}Cs	Industrial radiography calibration, clinical therapy		
^{140}Ba–^{140}La	Industrial radiography	Steel slag	
^{144}Ce–^{144}Pr	Clinical therapy		
^{192}Ir			
^{226}Ra with Be[a]	Neutron sources		Activation and other studies
^{227}Ac with Be			
^{210}Po, ^{239}Pu			
^{241}Am	Foil thickness measurements		Smoke detectors

[a] ^{226}Ra is no longer widely used.

One of the most valuable contributions of radioactive tracer techniques has been in the evaluation of wear and corrosion of key components in plants and machinery. In the majority of cases waste is produced as the component containing the radionuclide slowly wears, releasing radioactivity into the product or into a designated waste stream.

2.1.4. Universities and research establishments

Users of radioactive materials in universities and research establishments are most commonly involved in monitoring the metabolic or environmental pathways associated with materials as diverse as drugs, pesticides, fertilizers and minerals. The range of useful radionuclides is normally restricted and the activity content of the labelled compounds low, but at some research establishments more exotic radionuclides may be used. The radionuclides most commonly employed in studying the toxicology of many chemical compounds and their associated metabolic pathways are ^{14}C and ^{3}H, as they can be incorporated into complex molecules with considerable uniformity. Iodine-125 has proved to be very valuable in the labelling of proteins. A very wide spectrum of other radionuclides is available for research.

2.1.5. Decontamination and decommissioning

The tools and equipment used in facilities for nuclear applications, especially research reactors and facilities for the production of radioisotopes, may sometimes require decontamination so that maintenance can be performed. There are also times when a portion of, or the entire, facility may require decontamination so that it may be modified or upgraded. These decontamination operations result in the generation of secondary liquid and solid waste. The modification/upgrading operations may require decommissioning of various components of the facility and result in the generation of solid waste. This waste generally includes building materials and equipment components. The main features typifying decommissioning waste are the large sizes of the waste items and, in the case of research reactors, the presence of long lived radionuclides.

2.2. TYPES AND AMOUNT OF WASTE ARISING

2.2.1. Scale of radioactive waste production in Member States

The amount of radioactive waste produced in different countries varies widely, depending on the scale of the applications and the range of activity associated with particular nuclear materials. The associated activities and practices in different

TABLE V. CATEGORY SOURCES OF RADIOACTIVE WASTE

Category source	Typical use of radioactive materials in Member States
SIA	Single radioisotope application (typically in a hospital)
MIA	Multiple radioisotope applications
RRA	Research reactors and production of radionuclides coupled with their use in multiple applications
NPP	Nuclear power plants, research reactors and multiple radioisotope applications
NFC	Nuclear fuel cycle facilities, power plants, research reactors and multiple radioisotope applications

Member States may be grouped into five classes in accordance with the extent of the use of radioactive materials (Table V).

For the purpose of this report it is useful to classify countries into different categories according to the scale of their nuclear applications or activities and associated production of radioactive waste. This classification is illustrated in Table VI. A Member State classification may change when its level of nuclear programmes and associated waste generation move from one group to another.

Class A includes countries in which practices are represented by the application of a few sealed radiation sources used in industry and limited quantities of predominantly short lived radioisotopes used in medicine and research. The resulting waste can be a few spent sealed sources and small amounts of low level solid waste.

In a typical class A country the situation with waste arisings can be characterized by:

- — Short lived waste that will decay and be disposed of as non-radioactive waste;
- — A few spent sealed sources with long half-lives or relatively high activity levels, which usually are returned to the original suppliers;
- — Small quantities of waste containing weak beta emitting radionuclides (^{3}H, ^{14}C) in concentrations that allow dilution and discharge;
- — Very small quantities of solid waste.

Typical waste arisings and radioisotopes used in class A countries are listed in Table VII [1].

Class B encompasses countries in which radioactive materials are used in various applications, including a wide use of sealed sources for medical, industrial, agricultural and research purposes, as well as unsealed sources used, for example, in

TABLE VI. CLASSIFICATION OF COUNTRIES ACCORDING TO THE SCALE OF NUCLEAR ACTIVITY

Class	Typical characteristics
A	Countries with a very limited use of radionuclides (SIA)
B	Countries with multiple applications of radionuclides (MIA)
C	Countries with research reactors and multiple applications of radionuclides (RRA)
D	Countries with nuclear power plants (NPP)
E	Countries with nuclear power plants and other nuclear fuel cycle facilities (NFC)

TABLE VII. TYPICAL WASTE ARISINGS IN CLASS A COUNTRIES

Waste type	Arisings	Typical radioisotopes
Spent sealed sources	5–10 sources/a	^{60}Co, ^{137}Cs, ^{192}Ir, ^{241}Am, ^{241}Am/Be neutron, ^{226}Ra
Scintillation liquids	A few L/a	^{3}H, ^{14}C, ^{131}I
Hospital waste, dry	Less than 1 m^3/a	^{99}Tc^{m}, ^{125}I, ^{131}I
Decontamination waste (from a leaking radium source)	Less than 10 L/a	^{226}Ra, ^{222}Rn, ^{214}Po, ^{214}Bi

radiochemistry, radiobiology, diagnostic and therapeutic applications in medicine or for industrial radiography. The radionuclides used may include both those that are short and long lived. The waste generated consists primarily of spent radiation sources and various medical and biological wastes containing appreciable concentrations of short lived radionuclides, along with lesser amounts of long lived ones. Most radionuclides in this waste decays rapidly, permitting the waste to be handled as non-radioactive waste. The remainder will need to be treated, conditioned and stored as radioactive waste. Most of the waste will be in a solid form; however, smaller quantities of liquid waste may also be present.

In general, the types of waste generated by class B countries will be essentially the same as those produced by class A countries, except that the volumes will be notably greater and may therefore require the establishment of a central waste operating facility. Typical waste arisings for class B countries are shown in Table VIII [1].

TABLE VIII. TYPICAL WASTE ARISINGS IN CLASS B COUNTRIES

Waste type	Arisings	Typical radioisotopes
Spent sealed sources	20–100 sources/a[a]	^{60}Co, ^{137}Cs, ^{192}Ir, ^{241}Am, ^{241}Am/Be neutron, ^{226}Ra, ^{238}Pu, ^{85}Kr
Scintillation liquids	10 L/a	^{3}H, ^{14}C, ^{131}I
Hospital waste, dry; hospital waste, wet	1–3 m^3/a 10–50 L/a	^{99}Tc^{m}, ^{125}I, ^{131}I, ^{201}Tl, ^{90}Sr/^{90}Y, ^{198}Au, ^{65}Ni
Decontamination waste	1–2 m^3/a	^{226}Ra, ^{222}Rn, ^{214}Po, ^{214}Bi

[a] Larger quantities of spent sealed sources may already be accumulated at some facilities.

Class C includes countries in which, in addition to the activities mentioned for class B countries, research reactors are in operation. These reactors may also be used for radioisotope production. The waste generated (in addition to waste similar to class A and B countries) includes spent fuel elements, spent ion exchange resins, liquid waste from radioisotope production, items with induced activity and decommissioning waste. Management of these wastes usually requires the establishment of a centralized waste processing, storage and disposal facility, which in many cases will be associated with a research reactor site. Typical waste arisings for class C countries are shown in Table IX [1].

Nuclear power plant and fuel cycle waste produced by class D and E countries are outside the scope of this report and are therefore not discussed. However, in class D and E countries the same kinds of waste as in class A, B and C countries could be produced, and the approach for their processing would depend on the existing national waste management strategy and infrastructure.

2.2.2. Aqueous waste generation

Aqueous (liquid) radioactive waste is generated during research reactor operations and in other operations involving the application of radioisotopes (e.g. medicine, research and education). The type of liquid waste produced depends upon the particular operation being conducted and can vary extensively in both chemical and radionuclide content. Most operations, particularly the larger ones, also produce a variety of radioactive liquid wastes from locations such as showers, laundries and analytical laboratories, and from decontamination services. The specific activity of the waste generated depends upon which radioactive materials are used.

TABLE IX. WASTE EXPECTED ANNUALLY FROM NUCLEAR APPLICATIONS IN CLASS C COUNTRIES

Waste type	Volume (m^3/a)	Activity (Bq/m^3)	Typical radioisotopes
Liquids for treatment	50–100	10^4 to 4×10^9	^{55}Fe, ^{59}Fe, ^{58}Co (corrosion products)
Liquids for direct conditioning	0.5	Approx. 10^4	^{134}Cs, ^{137}Cs, ^{121}Te^m, ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{51}Cr, ^{59}Fe, ^{99}Tc^m, ^{111}In, ^{131}I
Organics (liquids)	0.1–0.3		
Solids (compatible)	20–80		^{3}H, ^{14}C, ^{111}In, ^{99}Mo, ^{99}Tc^m, ^{125}I, ^{131}I, ^{35}S, ^{24}Na, ^{32}P
Solids (non-compatible), (trash, sealed sources, radium needles, etc.)	5–10	Up to 10^{10}	^{3}H, ^{14}C, ^{111}In, ^{99}Mo, ^{99}Tc^m, ^{125}I, ^{131}I, ^{35}S, ^{24}Na, ^{32}P, ^{60}Co, ^{137}Cs, ^{192}Ir, ^{226}Ra
Solid biomedical waste	0.1–0.2	Approx. 10^6	^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{125}I
Ion exchange resins	0.5–1	(2–4) × 10^9	^{60}Co, ^{134}Cs
Total	100–200	10^4–10^{10}	

The volume of aqueous waste generated in class A, B and C countries accounts for an appreciable fraction of the total waste volume (Table X). Each type of application of radioactive materials is likely to result in aqueous waste that has certain characteristics in terms of radioactive isotopes present and their chemical nature. The aqueous waste arisings from different types of applications are described in a qualitative way in Table XI [3].

The composition of radioactive aqueous waste covers a wide range, both with regard to its activities and the presence of alpha emitting and beta/gamma emitting radionuclides. Some waste streams contain both. Many streams contain specific groups of radionuclides, others only one or two. For streams containing mainly short lived beta/gamma activity the effluents should be kept in storage. After decay to a specific activity within prescribed limits, they can generally be safely discharged to the environment.

TABLE X. VOLUMES AND ACTIVITIES OF AQUEOUS RADIOACTIVE WASTE GENERATED IN CLASS A, B AND C COUNTRIES

Category	Decay/dilution/discharge		Treatment/conditioning		Direct conditioning	
	m^3/a	GBq/a	m^3/a	GBq/a	m^3/a	GBq/a
Class A	5–10	40	—	—	—	—
Class B	10–50	200	1–5	0.1	0.1	0.5
Class C	100–400	400–2000	100–200	200–400	0.5	5

While specific activity and radiological safety are emphasized and are the primary reasons that these wastes are regulated, the chemical and in some cases the biological characteristics of them may influence the waste management option selection.

In some laboratories or facilities of a nuclear research centre, small volumes (10 to 100 L) of liquid effluents are generated that contain higher concentrations of radioactivity with long lived radionuclides. A typical example is decontamination liquid resulting from the generally infrequent decontamination of plant piping and equipment. These effluents can include crud (corrosion products) and a wide variety of solutions containing phosphates, citrates, tartrates, detergents, acidic products and ethylenediaminetetraacetic acid (EDTA). These effluents should be carefully segregated and collected in small bottles or containers. Mixing with other radioactive effluents or concentration by evaporation and precipitation is not advisable for this type of waste. The preferred option for processing this type of waste is direct conditioning, generally with cement [4]. The chemical nature of the waste may require special cement formulation (because, for example, high concentrations of EDTA interfere with the hardening of ordinary Portland cement).

2.2.3. Liquid organic waste generation

Radioactive organic liquid waste from medical, industrial and research centres forms a relatively small volume compared with other radioactive wastes. Typically, this waste includes oils, solvents, scintillation fluids and miscellaneous biological fluids. Table XII shows typical volumes of the different organic liquid waste produced per annum in class A, B and C countries [5].

2.2.3.1. Oils

Radioactive oil waste consists of lubricating oils, hydraulic fluids and vacuum pump oils. This type of waste generally contains only relatively small quantities of

TABLE XI. AQUEOUS WASTE CHARACTERISTICS BY SOURCE AND APPLICATION

Source	Typical radioisotopes	Chemical characteristics	Recommended treatment/disposal method
1. Nuclear research centres	Variable, with relatively long lived ^{59}Fe, ^{60}Co, ^{137}Cs, etc., mixed with short lived ^{24}Na, etc.	Generally uniform batches with nearly neutral pH from regeneration of ion exchange resins	Storage for decay and, if necessary, treatment by precipitation
2. Laboratories producing radioisotopes	Wide variety, depending upon production and purity of targets	(a) Small volumes of high specific activity and high chemical concentrations (b) Larger volumes of low specific activity	Segregate (a) and (b), store (a) in hot cells for interim decay then remove for further storage and/or treatment along with (b)
3. Radiolabelling and radiopharmaceuticals	^{14}C, ^{3}H, ^{32}P, ^{35}S, ^{125}I	Small volumes of variable but predictable chemical composition	Decay in storage, isolate low specific activity for disposal. Treat or solidify high specific activity ^{14}C waste
4. Medical diagnosis and treatment	^{99}Tc^{m}, ^{131}I, ^{85}Sr	(a) Large volumes of urine from patients (b) Small volumes from preparation and treatment	(a) Direct release to sanitary waste (b) Collection, decay and release
5. Scientific research	Variable, with much ^{14}C, ^{3}H, ^{125}I, and other short and long lived radioisotopes	Extremely variable	Segregate waste by chemical classes, specific activity and radionuclide. Decay storage prior to release. Individual waste containers taken to a central facility for treatment
6. Industrial and pilot plants	Depends upon application	Volumes could be large and chemical composition undefined	Storage for decay and release. Uranium and Th may require processing
7. Laundry and decontamination	Wide variety likely	Volumes large with low specific activity but containing complexing agents	Storage for decay. If treatment is required chemical pretreatment may be necessary

TABLE XII. TYPES AND VOLUMES OF CONTAMINATED ORGANIC LIQUIDS IN CLASS A, B AND C COUNTRIES

Liquid organic waste	Countries		
	Class A	Class B	Class C
Oil, lubricants			
Volume (m^3)	—	0.005	0.1
Activity (MBq/m^3)	—	30	300
Radionuclide	—	^{3}H, ^{14}C	^{58}Co, ^{60}Co, ^{137}Cs, ^{3}H, ^{14}C
Scintillation liquids			
Volume (m^3/a)	0.01	0.01–0.02	0.05
Activity (MBq/m^3)	30	30–50	300
Radionuclide	^{3}H, ^{14}C	^{3}H, ^{14}C	^{3}H, ^{14}C, ^{125}I, ^{32}P, ^{35}S
TBP-containing solvents			
Volume (m^3/a)	0.01	0.01	0.05–0.2
Activity (MBq/m^3)	30	30	<10 000
Radionuclide	U, Th + daughters	U, Th + daughters	U, Th + daughters
Extraction agents			
Volume (m^3/a)	—	—	0.01
Activity (MBq/m^3)	—	—	<30
Radionuclide	—	—	U, Th + daughters
Other organics			
Volume (m^3/a)	—	—	0.05
Activity (MBq/m^3)	—	—	300
Radionuclide	—	—	^{3}H, ^{14}C, ^{58}Co, ^{60}Co, ^{134}Cs, ^{137}Cs

beta/gamma emitting radionuclides, but may also contain trace quantities of alpha emitting radionuclides, depending on its origin. This waste generally arises from activities in nuclear research centres; tritium contaminated oils may also arise from various medical and industrial applications. Radioactivity levels for oils may vary widely, depending on the applications they are associated with.

2.2.3.2. Scintillation liquids

Scintillation liquids result from radiochemical analyses of low energy beta emitters, such as ^{3}H and ^{14}C. They typically consist of non-polar organic solvents such as toluene, xylene and hexane, but they may also include biological compounds such as steroids and lipids. Radioactivity levels are typically of the order of 350 MBq/m^3.

2.2.3.3. Solvents

Spent solvents may arise from solvent extraction processes. The most commonly used extraction solvent is TBP. TBP is diluted for the extraction process usually with a light saturated hydrocarbon, often dodecane or a mixture of paraffins. A variety of organic decontamination liquids and solvents, such as toluene, carbon tetrachloride, acetone, alcohols and trichloroethane, arise from various operations. Dry cleaning produces small quantities of perchloroethylene and Freon 112 waste. The gross alpha/beta activity of this waste is usually less than about 200 MBq/m^3.

2.2.4. Solid waste generation

Solid waste can be segregated into two main groups: compactible, combustible solid waste and non-compactible, non-combustible solid waste [6–8]. Other possible groups may be processible (by compaction or incineration) and non-processible waste. The largest volume of solid waste is general rubbish, which includes protective clothing, plastic sheets and bags, rubber gloves, mats, shoe covers, paper wipes, rags, towels, metal and glass [6].

Segregation should be preceded by an appropriate activity measurement and by distinguishing between waste that after decay storage can be disposed of with municipal refuse (i.e. waste contaminated by radionuclides with a half-life $\leq$100 days) and waste that needs treatment and conditioning. Considering the relatively small amounts of combustible waste, compaction should be the preferred volume reduction method. Incineration is technically much more complicated and should only be considered if large quantities of combustible waste can be incinerated in a continuous manner.

Table XIII presents an estimation of solid waste generation in class A, B and C countries.

The typical distribution of solid waste generated in research centres is:

- 70% compressible or combustible material, such as plastic fragments, paper and cloth, small metallic or glass objects, and miscellaneous (animal carcasses, wood, etc.);
- 20% hard materials, such as metal components, coating or lining fragments and items whose size normally calls for fragmentation;
- 10% debris resulting from plant conversion and operational incidents (concrete, soil, etc.).

TABLE XIII. ESTIMATED ANNUAL RADIOACTIVE SOLID WASTE GENERATION IN CLASS A, B AND C COUNTRIES

Category	Solid waste for treatment		Solid waste for direct conditioning	
	Volume (m^3/a)	Total activity (GBq)	Volume (m^3/a)	Total activity (GBq)
Class A	10–20	2	1–5	3
Class B	50	40	5	5
Class C	50–100	40–80	10	15

2.2.5. Wet solid waste generation

Wet solid waste, such as spent radioactive ion exchange resins, precipitation sludges and evaporator concentrates, is generated by the treatment of aqueous waste streams at nuclear research centres or at centralized waste processing facilities.

2.2.5.1. Spent ion exchange resins

Ion exchange media can be classified into two basic categories: inorganic ion exchangers (both natural and synthetic) and organic resins (mainly synthetic). Most commercial ion exchangers are synthetic organic resins typically consisting of polystyrene cross-linked with divinylbenzene. Spent organic and inorganic ion exchange media may require different treatment and conditioning options. Although regeneration of spent organic resin is possible, the preferred option is direct conditioning of spent resin, as regeneration results in the production of highly acidic and caustic radioactive liquids, which may be difficult to treat [9].

2.2.5.2. Precipitation sludges

The product of treatment of liquid radioactive waste by chemical precipitation and flocculation is a sludge containing most of the radioactivity; this can vary greatly in terms of its chemical and physical characteristics, depending on the specific process used (see Section 6.4). The chemical composition of the sludge differs from the initial waste owing to the addition of the precipitating chemicals.

2.2.5.3. Evaporator concentrates

Evaporator concentrates are produced through an evaporation process by which the volatile and non-volatile components of a solution or slurry are separated to reduce both the waste volume and the amount of radioactivity in a liquid effluent. Evaporation is most effectively used for radioactive liquids with high concentrations of salts or other impurities. The concentrate or bottoms product can range from 15 wt% solids to a virtually dry powder or cake, depending on the evaporator type and efficiency and on the chemical composition of the waste stream.

2.2.6. Biological waste generation

Biological radioactive waste arises from biological, research and teaching/training practices. This waste includes animal carcasses, contaminated body fluids and animal tissues. The inclusion of materials having a biological origin clearly distinguishes this type of waste from inorganic materials. A primary example of biological waste is the waste from research involving animals. All discharges (e.g. faeces, urine and saliva) from animals used in research involving radioactive materials must be considered to be potentially contaminated. Animal cage containers must be treated as contaminated until monitored and declared free from contamination [10].

2.2.7. Medical waste generation

Medical radioactive waste may be defined as radioactive waste arising from diagnostic, therapeutic and research applications in medicine. In addition to being contaminated by radioactivity, medical waste, like biological waste, can have infectious, pathological and other hazardous properties. In many instances the potential additional hazard, either from the waste's chemical, biological or physical properties, is greater than the radiological hazard [2].

The following types of radioactive waste may occur as a result of the use of radionuclides in medicine:

— Spent radionuclide generators and spent sealed radiation sources;
— Anatomical and biological waste (e.g. body parts, tissues, organs, fluids and excreta from patients administered with radionuclides);
— Miscellaneous aqueous and organic liquids, and radioactive solutions;
— Miscellaneous solid dry waste (e.g. gloves, paper tissues and equipment parts);
— Miscellaneous waste posing a puncture hazard (e.g. needles, broken glass and nails).

3. WASTE CLASSIFICATION

3.1. GENERAL CONSIDERATIONS

Classification of radioactive waste can be helpful at any stage, from the origination of the raw waste through to its collection, segregation, treatment, conditioning, storage, transportation and final disposal. Classification systems may be derived from different perspectives, for instance safety related aspects, the physical/chemical characteristics of the waste, process engineering demands or regulatory issues [11, 12].

Some of the important waste properties and criteria to be considered for various classification schemes are [11]:

- The origin of the waste.
- The radiological properties: half-life, heat generation, activity and concentration of the radionuclides, surface contamination, and the dose factors of the relevant radionuclides.
- The physical properties: physical state (e.g. solid, liquid or gaseous), size and weight, compactibility, dispersibility, volatility, solubility and miscibility.
- The chemical properties: potential chemical hazard, corrosion resistance/corrosiveness, organic content, combustibility, reactivity, gas generation and sorption of radionuclides.
- The biological properties: potential biological hazards (e.g. infection and putrefaction).

3.2. WASTE CLASSIFICATION FOR HANDLING, TREATMENT AND STORAGE

The radioactivity level in waste may affect its handling, treatment and interim storage options owing to its shielding requirements. To improve international communication, a simple classification system for radioactive waste based on arbitrary activity concentration levels of liquid waste and radiation dose rates on the surface of solid waste was recommended by the IAEA in 1970 [12].

In the new classification system proposed in 1994 [11], the principal waste classes include exempt, low and intermediate level waste, which may be subdivided into short lived and long lived waste, and high level waste. Boundary levels between waste classes are presented as orders of magnitude; typical characteristics of waste classes are summarized in Table XIV.

TABLE XIV. TYPICAL CHARACTERISTICS OF WASTE CLASSES

Waste class	Typical characteristics	Disposal options
1. Exempt waste (EW)	Activity levels at or below the clearance levels given in Ref. [13], which are based on an annual dose to members of the public of less than 0.01 mSv	No radiological restrictions
2. Low and intermediate level waste (LILW)	Activity levels above the clearance levels given in Ref. [13] and thermal power below about 2 kW/m^3	Near surface or geological disposal facilities
2.1. Short lived waste (LILW–SL)	Restricted long lived radionuclide concentrations (limitation of long lived alpha emitting radionuclides to 4000 Bq/g in individual waste packages and to an overall average of 400 Bq/g per waste package)	Near surface or geological disposal facilities
2.2. Long lived waste (LILW–LL)	Long lived radionuclide concentrations exceeding the limitations for short lived waste	Geological disposal facilities
3. High level waste (HLW)	Thermal power above about 2 kW/m^3 and long lived radionuclide concentrations exceeding the limitations for short lived waste	Geological disposal facilities

3.3. CLASSIFICATION FOR RELEASE FROM REGULATORY CONTROL

3.3.1. Exemption and clearance concept

The concept of exemption (or clearance) was pursued for several years through IAEA working groups under a general concept of ‘de minimis’, mainly in relation to radioactive waste disposal in marine and terrestrial environments [14, 15]. In 1984, in co-operation with the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA), a new programme was started with the specific objective of (a) developing principles for exempting radiation sources and practices from regulatory control and (b) developing guidance on the application of the principles to practical problems. This culminated in 1988 with the publication of Safety Series No. 89 [16], which contains results representing an international consensus on the subject.

Some types of sources of ionizing radiation may not be subject to regulatory control, either because they are not amenable to such control and therefore excluded from the regulatory process or because they present such a low risk that control by regulatory processes would be a waste of resources. In the latter case, two categories can be distinguished:

- Radiation sources which never enter the regulatory regime, that is control is not imposed;
- Radiation sources which are released from regulatory control, that is control is removed.

Sources in the first category are excluded from regulatory control by a process called exemption. The corresponding levels of activity or activity concentration are called exemption levels. In the second category the release of sources from control is called clearance. The amount of material involved in clearances can be substantial and is generally greater that those involved in exemptions. The corresponding levels of activity or activity concentration are called clearance levels. The distinction between exemption and clearance in IAEA publications has been made only recently [17], and so in the literature terms such as exemption and exempt are often used in circumstances where terms such as clearance and cleared would currently be used.

The IAEA has recently published reports dealing with the problems involved in applying exemption principles to waste arising from the use of radionuclides in medicine, industry and research [17]. In these publications methods for deriving exemption levels (clearance levels) are described and examples for calculating these levels are given.

Various national and regional groups have also been studying exemption principles and their application. National regulations have been developed in various countries based on these international guidelines, and recommendations have been made on applying then to local conditions. Thus a substantial base of experience now exists; clearance levels have been proposed in various countries for application to the most important low level waste streams from the nuclear fuel cycle and from the application of radioisotopes in medicine, research and industry.

3.3.2. Requirements for release to the environment under authorization

Before attempting to select and design a waste treatment system the restrictions or limits on releasing liquid and gaseous waste effluents need to be understood. Determination of these limits is performed differently in various countries, but always requires an extensive analysis by both the waste producer and regulatory body to arrive at an agreement that releases are acceptable. The basic principles for establishing release limits are set out in IAEA Safety Series Report No. 77 [18]. Essentially, this states that practices involving a release of radionuclides to the environment should be optimized; that is, that the associated radiation doses to the public and to workers should be as low as reasonably achievable (ALARA), and that doses should be below specified limits.

The evaluation of these radiation doses may involve the use of environmental models in which the transport of radionuclides to humans through the processes of atmospheric dispersion, deposition and movement through terrestrial and aquatic systems and food chains is represented. The limitation of doses to members of the public is achieved by limiting the dose to an identified critical group; that is, a group of persons who, by virtue of their location, habits, etc., are representative of those most highly exposed in the population. This modelling is generally referred to as pathway analysis.

The International Committee on Radiological Protection (ICRP) prescribes dose limits, but since an individual may be exposed to more than one source of radiation only a fraction of the whole dose limit should be assigned to any given practice. In its most recent recommendations [19] the ICRP introduced the term dose constraint as the fraction of the dose limit that may be applied to a single practice. The dose constraint should be used as the upper bound for the optimization process. The values of the dose constraint should be set by national authorities.

There may be several different options for managing a waste stream, each of them involving some discharge to the environment, for example direct discharge, discharge after treatment and discharge after storage. Some of the options initially considered may be discarded for non-radiation protection reasons, for example on grounds of cost or for operational reasons, or for the control of other chemical or biological hazards.

Once an agreement has been reached as to the suitability of a proposed waste treatment scheme, a discharge authorization should be provided by the national authority to the waste producer; this should detail the specific requirements to be met at the point of discharge in terms of:

- The maximum permissible radioactivity concentration in the effluent;
- The flow rate of the effluent and total volume;
- The daily, monthly and/or yearly radioactivity discharge levels both for total activity and for individual or groups of radionuclides.

3.4. CLASSIFICATION FOR WASTE DISPOSAL

For radioactive waste that cannot be released to the environment, special disposal facilities (repositories) must be provided. For radioactive waste disposal the most important radiological classification parameter is the concentration of long lived radionuclides, especially of alpha emitters [20]. The new waste classification system proposed by the IAEA considers a qualitative classification for radioactive waste [11]. The proposed categories take account of properties such as half-life and heat generating capacity. The categorization, shown in Table XIV, assumes that the waste has been appropriately conditioned and packaged.

Requirements for class 1 waste, exempt waste, are described in Section 3.3. Class 2 waste is suitable for shallow ground disposal as it has insignificant alpha activity and heat output, and intermediate and low radiotoxicity. With the exception of spent sealed sources, wastes generated in developing countries are essentially within these two categories. For radioactive waste containing more than a specified amount of long lived radionuclides, significant engineered facilities (e.g. deep geological repositories) are required.

Many developed Member States have quantitative regulations classifying their wastes [21, 22]. The regulations usually apply restrictions on the concentration of radionuclides in individual packages and in the waste as an average. The values are determined by means of a safety assessment in which the scenarios and routes by which humans could be exposed during the operation of a repository and after its closure are analysed. It is not usually considered possible to give general values for gamma/beta emitters as they vary, depending on the characteristics of the disposal site. However, the limiting values for alpha emitters are less variable, and these values have been published [22].

4. COMPONENTS OF A COMPREHENSIVE WASTE MANAGEMENT SYSTEM

Member States, especially those that have already established nuclear research centres that produce radionuclides for medical and research purposes, need to establish a national waste management policy and a systematic national waste management programme. A national waste management programme should include at least the following elements:

- Development and adoption of appropriate legislation and regulations [23–25];
- Effective planning, implementation and enforcement procedures;
- The provision of adequate facilities for radioactive waste management;
- Appropriate training plans for national enforcement officers, plant operators and managers;
- Public awareness education programmes.

4.1. NATIONAL POLICY

A national policy for radioactive waste management is a fundamental cornerstone of a radioactive waste management system [23]. The roles and responsibilities of the organizations involved in its implementation should be clearly identified and the necessary resources (organizational, financal, technical and advisory) should be provided to administer the policy.

The national waste management policy should be expressed so as to protect people and their environment from undue exposure to ionizing radiation from radioactive waste by the application of up to date internationally accepted waste processing recommendations and safety requirements. In establishing and keeping the policy and programmes under review, governments should be advised by appropriately qualified persons whose combined expertise covers all relevant disciplines. Ideally, these advisors should be independent of the waste generators and operators of waste management facilities.

While the national policy should be created based on internationally accepted scientific principles, it should also consider local social conditions or cultural values and traditions. The national policy should generally be established at the highest level of government, usually at the national executive level. Recognizing that governments can change, or change direction very quickly, the national policy should be insulated as much as possible from frequent political and bureaucratic changes. Failure to provide such political insulation will result in an unstable regulatory environment that may compromise the overall effectiveness of the waste management programme. The national policy should also be adaptive, so that it can be applied to new circumstances or modified if legitimate reasons emerge for doing so. It should be proactive, rather than reactive.

The national waste management policy should form the basis for legislation and regulation of waste management activities. The policy may state preference for one management option over another (e.g. storage for decay then disposal as non-radioactive waste, versus immediate disposal as radioactive waste) and define the funding and management responsibilities for the programmes and the legal/jurisdictional roles for various government departments.

4.2. LEGISLATION AND REGULATIONS

Waste management legislation should be introduced together with general radiation protection, nuclear energy or other relevant national legislation (e.g. for industrial safety and environmental protection). To achieve acceptance by a majority of the population, the waste management legislation should be constructed according to the national legal, technical and cultural traditions. It may be periodically reviewed and modified as a result of changes in the national waste management policy.

Waste management regulations should generally be drafted by the appointed regulatory agency, based on the national policies and legislation. Following modification, approval and enactment by the appropriate assemblies, the legislation should form the basis for the regulations. The legislation can establish definitions, list technical limits on various waste properties and/or quantities (or specify the process to establish them), and establish legal mechanisms for enforcement, exclusion or exemption for various forms of waste.

Documented enforcement procedures should be formally created by the regulatory agency based on the legislation and regulations. These procedures, used by regulatory officers, need to ensure consistent application and interpretation of the regulations. It is also important to maintain a record of previous decisions and interpretations so that these can be consistently applied in the future.

National legislation is of no practical value if it does not have an organization with enough resources for its implementation. Enforcement of the legislation and regulations should be carried out by a regulatory body, which should have the authority to impose sanctions or to suspend operating licences if serious violations of the law or regulations are made by the operators.

4.3. WASTE MANAGEMENT FACILITIES

4.3.1. General

It is the responsibility of the regulatory body to ensure that licence holders have all the necessary equipment for waste processing and site/environment monitoring, and that it is suitable for the licensee's purpose. The implementation of a waste management programme in compliance with national policy and established regulations requires adequate technical capabilities; these include facilities, installations and personnel. The facilities should be constructed to comply with the specific requirements, existing or foreseen, for local or national waste management.

Since many individual producers of waste may not have sufficient interest or expertise in waste management, it may be appropriate to consider having a central waste management facility where the necessary expertise, infrastructure and quality assurance capability can be built up. Accordingly, this concept envisages that waste from a variety of producers will be transported to the central facility for subsequent management. In many countries the national nuclear research organization will be the central agency responsible for radioactive waste management, with regulation provided by an appropriate government department.

The impact on waste management facilities from planned changes in the use of radionuclides, notably an increased usage or new applications, must be analysed and all necessary modifications implemented or required new facilities made ready in a timely manner to comply with the changed requirements when they occur. In order to manage short term increases in waste volumes to be processed, for example as a result of an incident, the capacity of facilities should be higher than required for normal operation. The extent of the increased capacity should be based on an optimization of waste treatment methods, efficiencies and radiation protection. It should be the responsibility of the user to provide it, and of the regulatory body to determine that it is adequate for its purpose. Often a regulator will require, as part of the licensing conditions, the operator of a facility to maintain a minimum reserve capacity empty at all times to cover emergency requirements.

The waste management facility should secure for itself the best equipment available. This, however, does not mean that the most expensive and sophisticated equipment should be procured; in most cases it is preferable to have less sophisticated and less costly equipment but which is reliable and performs its required functions adequately. Such factors as service and maintenance facilities, the availability of spare parts, etc., should also be considered.

The waste management facility should determine the location of equipment that may be needed in emergencies and ensure that it is readily available. Examples of such equipment are additional radiation protection monitors, shielded transport containers, decontamination equipment and remote handling devices.

The central facility must have the necessary financial resources for the safe management of the waste; this should be considered during the initial stages of planning for the use of radionuclides. The government should also ensure by appropriate means that money for the safe management of radioactive waste is available for situations when an operator, for whatever reason, no longer has the financial resources properly to handle radioactive waste.

4.3.2. Planning considerations

Planning, implementing, managing and enforcing a waste management programme requires careful thought. Several factors must be taken into consideration:

- Care should be taken to minimize risk both to the natural environment and to the public.
- Where it is not yet possible to undertake all of the management steps from waste origination to final disposal, it is advisable that steps be taken to avoid closing off later options, since some may require substantial additional cost and radiation dose penalties.
- If the dilute and disperse option open for some aqueous and gaseous wastes is not appropriate, strategies incorporating confinement and concentration of the waste should be considered.
- The preferred processes should be considered taking into consideration the local availability of equipment and resources. This is especially true in developing countries, where highly sophisticated equipment may be difficult to obtain and maintain in a proper working condition.

- Following immobilization, a complete waste management strategy should include both storage and disposal. However, in developing countries the quantities of waste for disposal may not be sufficient to justify construction of a waste repository. Consequently, the conditioned waste may have to be stored for an extended period of time.

The overall waste management scheme should be properly planned to consider collection and segregation of wastes, their volume reduction and appropriate conditioning into a form suitable for future handling, transportation, storage and disposal. Pertinent technological steps in managing radioactive waste are detailed in Fig. 1.

4.3.3. Waste minimization

Minimization of radioactive waste generation is a vital requirement that must be addressed at all stages of the design and operation of facilities that use or produce radioactive materials.Waste minimization generally encompasses three main areas [26]:

- Source reduction, which includes any activity that reduces or eliminates the generation of radioactive waste within a process (including segregation of waste and prevention of contamination spreading);
- Recycling and reuse of valuable materials produced as by-products of the process;
- Treatment to reduce the volume of a radioactive waste without recovery or reuse of the material.

Of these three concepts, source reduction is generally the most important in class A, B and C countries.

To facilitate subsequent handling, treatment and storage, it is strongly recommended that waste be segregated at the place of origin. It is essential to segregate inactive waste from active waste and to isolate low specific activity waste and that containing short half-life radioisotopes from that requiring further treatment.

4.3.4. Pretreatment

Segregation is one of the most important pretreatment methods in managing waste originating in class A, B and C countries. The collection of waste should provide for segregation according to half-life and chemical composition in order to facilitate subsequent storage for decay, or treatment, conditioning and disposal.

Waste containing long lived radionuclides generally requires a more complex technological infrastructure. Waste treatment, conditioning, storage and eventual

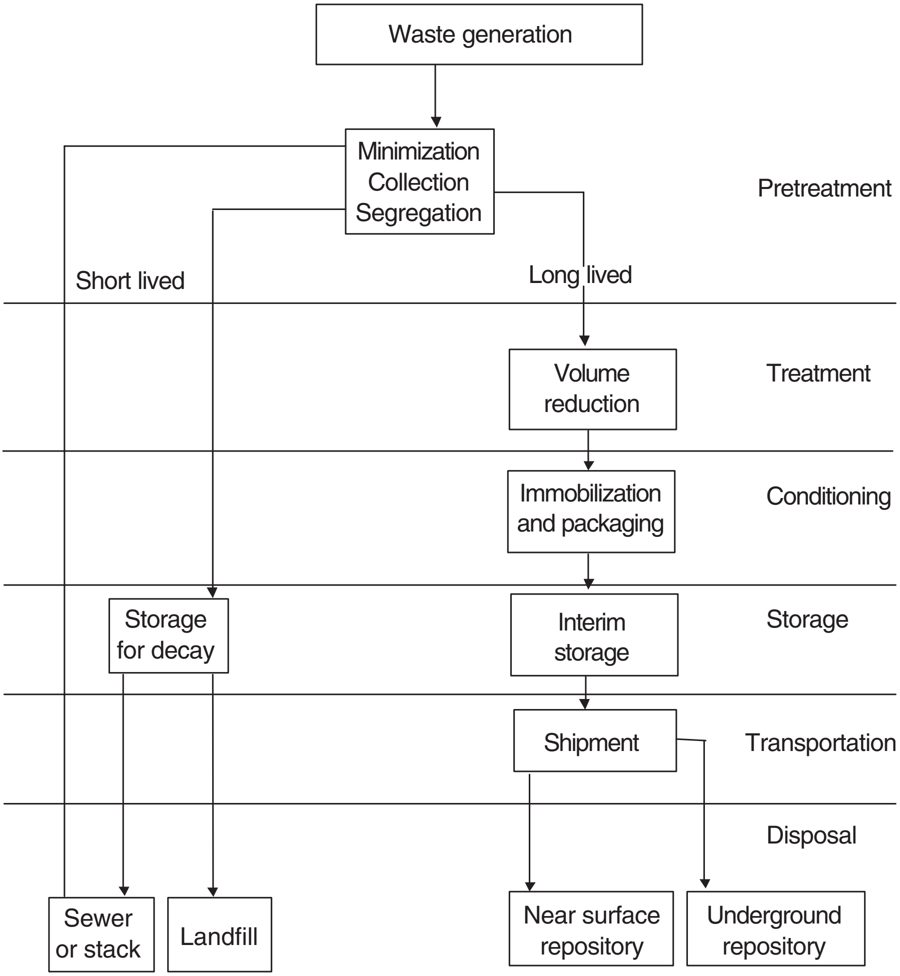


FIG. 1. Technological steps for managing radioactive waste.

disposal may all be required, and in turn will require appropriate facilities, equipment and training of personnel.

Further details of pretreatment techniques and practices can be found in Ref. [27].

4.3.5. Treatment

Treatment of waste involves operations intended to benefit safety and/or economy by changing the characteristics of the waste. The waste volumes in class A countries are usually small and do not require any special treatment. For class B countries simple compaction equipment may be sufficient for solid low level waste, whereas liquid waste can either be stored for decay or directly solidified. In the case of class C countries solid waste may be treated by compaction or incineration, and liquid waste concentrated by means of chemical precipitation, evaporation or ion exchange techniques.

4.3.6. Conditioning

It is generally agreed that the safe management of radioactive wastes may be brought about if they are transformed into a solidified form through an appropriate conditioning technique. Conditioning of waste is defined as those operations that produce a waste package suitable for handling, transportation, storage and/or disposal. Conditioning may include the conversion of the waste into a solid waste form, enclosure of the waste in containers and, if necessary, providing an overpack. In the case of class B countries simple equipment operated on a laboratory or pilot plant scale will be sufficient to condition small amounts of liquid waste for storage and/or disposal. Class C countries may require a small dedicated facility for the treatment of liquid waste and for the conditioning of concentrates and spent ion exchange resins from research reactor operations and various other applications. These operations, which involve immobilizing radioactive waste and providing adequate packaging, are mainly based on the use of cementation, although there are also other appropriate immobilization methods, as described in Sections 9 and 10.

4.3.7. Storage

All class A, B and C countries require storage facilities to accommodate waste arisings prior to their release or disposal. Two types of waste storage may be required:

- For raw waste awaiting treatment or decay for release,
- For conditioned waste awaiting disposal.

Only simple storage facilities, such as a separate room or part of a room within a hospital or research complex, are required in class A countries; more complicated storage facilities may be needed in class B and C countries. Storage facilities should be well constructed, with inner surfaces that can be easily decontaminated, and provided with security measures to prevent the intrusion of unauthorized persons. In addition, storage facilities in class C countries accommodating long lived waste and/or spent fuel may need additional provisions, such as dosimetric control and ventilation [28].

4.3.8. Transportation

In countries where the movement of waste to a centralized site is practiced, special attention needs to be paid to transportation. The waste packages, means of transportation and overall transport conditions should meet the requirements set forth in the internationally accepted IAEA regulations [29]. This also applies for the transportation of spent sources back to the supplier, and of packaged waste for disposal in a regional or national repository.

In many cases, where the amount or activity of the waste is low, there is no obligation to use a specifically designed vehicle for transportation. However, for transboundary movements of radioactive materials, the need for special agreements may arise.

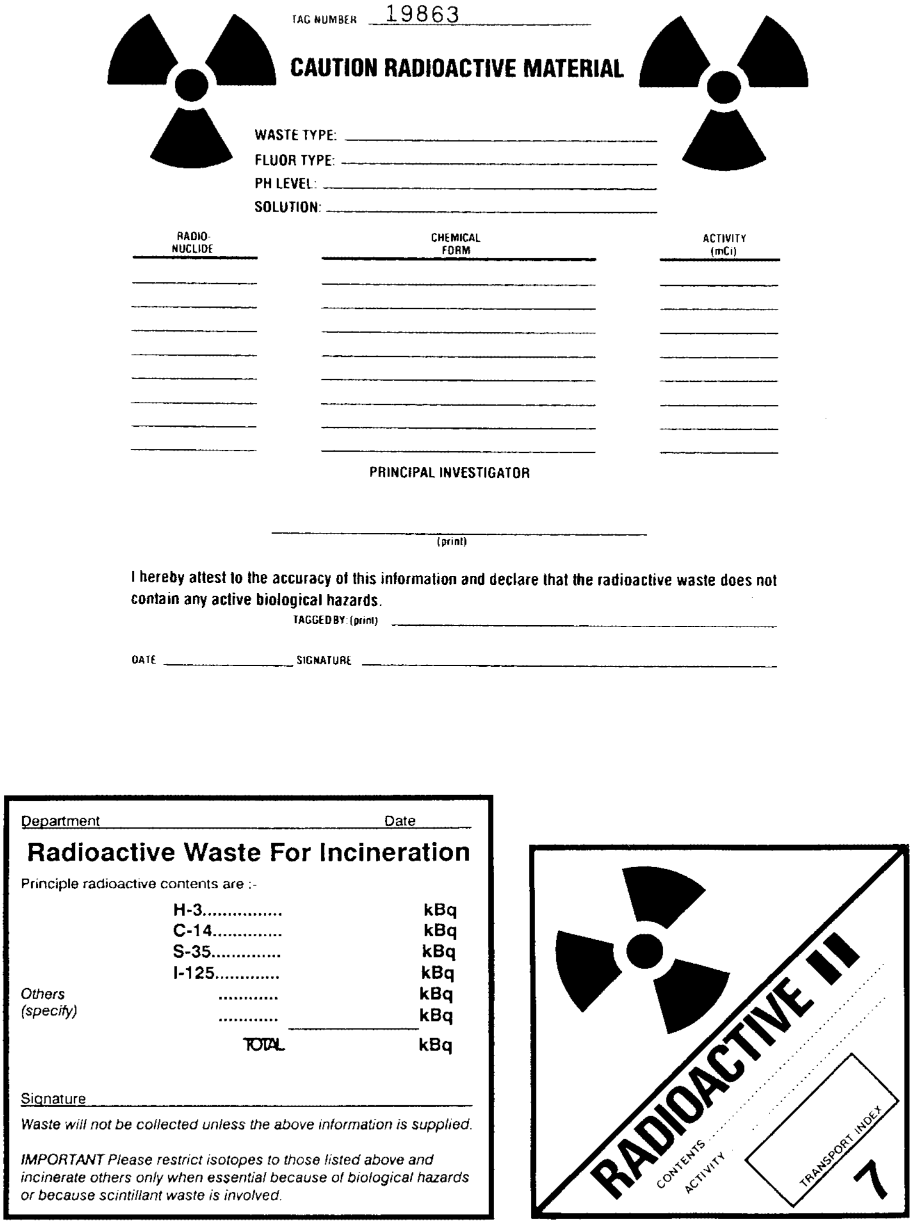
4.3.9. Disposal

Disposal of radioactive waste involves placing it in an approved, specified facility (e.g. a near surface or geological repository) without the intention of retrieval. Disposal may also include the approved direct discharge of effluents (e.g. liquid and gaseous waste with very low activity) to the environment, with subsequent dispersion. For countries with minimum waste quantities originating from few practices, it may be inappropriate to construct and operate a national repository. It should be noted that when sealed sources are originally supplied by a foreign vendor, return of the spent source to the original country of supply is the best solution.

In the case of class A and B countries, disposal options may include landfill of short lived low level waste. For long lived spent sources, notably ^{226}Ra, that cannot be returned to the vendors, as well as other conditioned wastes with activity contents exceeding the criteria for disposal in a national near surface repository, controlled storage is presently the only practicable option. Geological repositories for these waste categories are being developed in several countries, but would possibly not be justified in terms of cost for non-nuclear power countries with only modest amounts of waste. The long term solution for such countries may involve international co-operation in geological disposal [30, 31].

4.3.10. Documentation

A well designed waste management strategy enables an establishment to keep records that integrate and document the information obtained in all phases of waste management. Full traceability of waste up to the stage of storage or disposal is essential. A key step for such a strategy is that an appropriate description of the waste is available when it is collected at the point of origin. This essential information can be most conveniently collected by the use of appropriate labels affixed to the waste packages or containers (for examples see Fig. 2). The documentation requirements and level of detail are normally specified by the national regulations.



TAG NUMBER 19863

CAUTION RADIOACTIVE MATERIAL

WASTE TYPE: ____________

FLUOR TYPE: ____________

PH LEVEL: ____________

SOLUTION: ____________

RADIO-NUCLIDE	CHEMICAL FORM	ACTIVITY (mCi)

PRINCIPAL INVESTIGATOR

____________ (print)

I hereby attest to the accuracy of this information and declare that the radioactive waste does not contain any active biological hazards.

TAGGED BY (print) ____________

DATE ____________ SIGNATURE ____________

Department ____________ Date ____________

Radioactive Waste For Incineration

Principle radioactive contents are :-

	H-3................	kBq
	C-14..............	kBq
	S-35..............	kBq
	I-125.............	kBq
Others	....	kBq
(specify)	....	kBq
	TOTAL	kBq

Signature ____________

Waste will not be collected unless the above information is supplied.

IMPORTANT Please restrict isotopes to those listed above and incinerate others only when essential because of biological hazards or because scintillant waste is involved.

RADIOACTIVE II

CONTENTS ....

ACTIVITY ....

TRANSPORT INDEX

7

FIG. 2. Typical information labels.

4.4. CONSIDERATIONS FOR A COST EFFECTIVE SYSTEM

Although the basic principle should be that waste generators bear the costs incurred by their activities, the responsibility for ensuring the necessary financial resources for the execution of waste management programmes rests with the state. The financial requirements broadly comprise two categories. The first category covers the direct costs involved in carrying out the various operational steps such as handling, transport, conditioning and storage. These costs can be allocated to the respective waste generators and operators. The second category covers the indirect costs, such as those of the state and regulatory functions.

Any waste management plan should include cost estimates to be used for forming the basis for funding proposals consistent with the national waste management system, and that describe a financing mechanism using the provisions included in the legal framework of the country. This financing mechanism could provide means to allow the charges borne by some categories of waste generators, such as hospitals, universities and research institutes, to be subsidized.

5. STORAGE OF UNCONDITIONED WASTE

5.1. GENERAL REQUIREMENTS

Waste storage facilities for unconditioned liquid and solid radioactive waste must provide the following [28]:

- Operational convenience, for example allowing the accumulation of waste so as to facilitate the more cost effective use of treatment facilities, transportation and disposal routes;
- Safe and secure retention during a period long enough to permit radioactive decay prior to further radioactive waste management steps, for example storing shorter lived contamination in untreated waste prior to its disposal or discharge within exemption or clearance limits authorized by the national regulatory organization;
- Efficiency of the storage operation, with segregation of different waste categories, record keeping and easy retrieval permitting efficient further management of the waste;
- Verification and/or checking of individual packages.

5.1.1. Storage at radioisotope user establishments

Unconditioned waste is likely to be stored initially in the establishment where it is created. The waste must be segregated there and prepared for decay and/or further treatment or transportation in accordance with the acceptance criteria of the centralized radioactive waste management facility to which it may be subsequently transferred, or for disposal according to the selected route.

At the user establishment the storage requirements can be fulfilled in stores appropriate to the type of operation involved, normally in simple storage areas ranging from single secure cabinets or lockable wheeled bins to one or more dedicated rooms. Efficient operation of the store is essential to avoid the unnecessary accumulation of waste in work areas. This necessitates a planned system of collection and transfer of waste to the store in a well documented orderly fashion, and keeping information to be used for future management. All waste should be segregated and accumulated in containers that are suitable for further safe handling in line with future management proposals, taking into account factors such as robustness or biodegradability of containers, as required.

5.1.2. Storage at radioisotope production facilities

Generally, in routine radioisotope production facilities limited storage of liquid and solid waste is incorporated as part of the plant's design. Quantities of up to intermediate level waste will arise that will require local storage for decay of the predominantly short lived contaminants, before handling and transfer for treatment or disposal. Larger radioisotope producers need to install special storage facilities adjacent to the hot cells. Solid waste arising from radioisotope production may require several months of decay storage prior to release or further processing.

5.1.3. Storage at research reactors

In developing countries most reactor facilities have some waste storage arrangements integrated into their original design. Cleanup of the primary circuit cooling water using normal ion exchange processing gives rise to a small amount of waste requiring treatment and conditioning.

If the reactor cooling water is treated by the ion exchange process without regeneration, then the spent ion exchange media is likely to be radioactive waste approaching the intermediate activity level, which requires remote handling, shielding or in situ decay storage before manual handling. When the ion exchange media is regenerated, the small proportion of liquid waste containing the majority of the activity should be stored for subsequent treatment.

5.2. SPECIFIC REQUIREMENTS FOR THE STORAGE OF BIOLOGICAL AND MEDICAL RADIOACTIVE WASTE

Storage of unconditioned biological and medical waste often necessitates low temperature refrigeration, with temperatures typically –18 to –22°C. For prolonged storage at a centralized radioactive waste management facility beyond two or three years the waste should be stored at –70°C to minimize low temperature putrefaction.

Specific requirements for the refrigerated storage of unconditioned biological and medical wastes includes:

- Consideration of offensive odours from unconditioned waste, such as those that arise from food waste (e.g. from patients treated with therapeutic levels of radioiodine).
- Control of insects and rodents, which can present a serious threat to the containment of unconditioned packages of radioactive biological waste. The consumption of waste and dispersion through insect/rodent excretions can result in the spread of both radioactive contamination and potentially infectious materials.
- Ease of closure/sealing of the radioactive waste packages to prevent dispersion/seepage of contents.
- Ability of the packaging to withstand, without deterioration, the full range of temperature variations it is likely to encounter, such as the ability to withstand freezing without becoming brittle and liable to fracture.

Considerations for the design of organic liquid storage facilities include chemical hazards, fire protection, containment of spills and control of ventilation to prevent the buildup of harmful vapours.

5.3. DECAY STORAGE

When possible, and if permitted by the non-radioactive risks, advantage should be taken of the opportunity to avoid treating radioactive waste by carefully organizing the decay storage of shorter lived contaminated waste. Volatile or combustible waste presenting a hazard through fire, biological instability or toxicity are the main risk factors to be taken into consideration.

Decay storage for the common short lived radioisotopes is normally routinely applied to segregated low level waste from radionuclide users in hospitals, universities, research laboratories and other institutions. At radioactivity concentrations of 3.7 to 37 MBq/m^3 (0.1 to 1 mCi/m^3), decay storage of ten half-lives (giving a reduction of greater than 1000) potentially reduces the residual radioactivity content to below the limits for unconditional release/disposal.

Table XV gives the times (in years) for reduction in activity by factors of 10 to 10^6 for commonly used short lived radionuclides. Large reduction factors are achieved within short periods for very short lived radionuclides (e.g. a factor of 10^6 in five days (1.4×10^{-2} a) for $^{99}Tc^{m}$). For such short lived radionuclides there are not likely to be problems with discharge limits at the clearance level. Very short storage periods provide adequate decay, even at the lower limits for clearance. Problems arise for radionuclides with half-lives of between about six weeks to one year, but the activity reduction required is also a factor to be considered. For ^{45}Ca, of half-life 0.45 years, a period of nine years is required for a 10^6 reduction. Storage over such a long period may not be judged appropriate because of the risks associated with the long interim storage period.

The practical implementation of decay storage requires the operation of a protected, selective storage capacity with matching identification and other administrative procedures. This ensures that packages are stored for the correct length of time and the correct package is retrieved for disposal. Usual radiological protection requirements should apply regarding the handling of active or potentially active materials, even in the simplest facility.

The containers used for storing unconditioned waste are normally reusable 200 L drums with a lid firmly held in place by a metal clamp. The inner coating of the drum is suitable for cleaning with disinfectant or decontamination solutions.

Table XVI illustrates the records that may need to be maintained for radionuclides placed in decay storage. Completion of the records involves consideration of the features of the waste. At the time of receipt the duration for decay storage should be evaluated. In using the example given in Table XVI and consulting Table XV, after 47.5 days (1.3×10^{-1} a) the waste will be below 100 kBq/kg (with a mass of 1 kg the total activity is therefore 100 kBq) and thus will have a total activity less than 370 kBq. Assuming ^{32}P is of moderate radiotoxicity then, after this time, the waste will conform to the exemption criteria given in Section 3.

This is only an example application of storage for decay criteria. Any real calculation would also need to take account of specific national criteria and regulations.

5.4. DESIGN FEATURES FOR AN INTERIM STORAGE FACILITY

5.4.1. General

Developing Member States will not usually require a substantial separate building as a store for untreated waste. However, in the event of a backlog and no

TABLE XV. TIMES FOR SELECTED RADIONUCLIDES TO DECAY TO SPECIFIED LEVELS

Radionuclide	Decay constant (a^{-1})	Time [a] (in years) for reduction in activity by a factor of:					
		10	10^2	10^3	10^4	10^5	10^6
^{32}P	1.8×10	1.3×10^{-1}	2.6×10^{-1}	3.9×10^{-1}	5.2×10^{-1}	6.5×10^{-1}	7.8×10^{-1}
^{45}Ca	1.5	1.5	3	4.5	6	7.5	9
^{99}Mo	9.2×10	2.5×10^{-2}	5.0×10^{-2}	7.5×10^{-2}	1.0×10^{-1}	1.25×10^{-1}	1.5×10^{-1}
^{99}Tc^{m}	1.0×10^{3}	2.3×10^{-3}	4.6×10^{-3}	6.9×10^{-3}	9.2×10^{-3}	1.2×10^{-2}	1.4×10^{-2}
^{125}I	4.1	5.6×10^{-1}	1.1	1.7	2.3	2.8	3.4
^{131}I	3.2×10^{-1}	1.7×10^{-1}	3.4×10^{-1}	5.0×10^{-1}	6.7×10^{-1}	8.4×10^{-1}	1.0
^{192}Ir	3.4	6.8×10^{-1}	1.36	2.0	2.7	3.4	4.1

[a] Note: The above table is calculated from the following formula:

$$T = \frac{\ln R}{\lambda}$$

where T is time in years; λ is the decay constant; R is the reduction factor in 10^n; ln is the natural logarithm (Naperian).

TABLE XVI. EXAMPLE OF A DECAY STORE RECORD

Waste item number	Date received	Radionuclide	Activity at receipt	Description	Storage location	Date for disposal as exempt waste or cleared waste; disposal route	Disposal completed
1	1 July 1990. Signature of store manager	^{32}P	1 MBq	Contaminated cotton swabs and plastic sealed in a plastic container, mass 1 kg approx.	Bay 1, aisle A, location 2	1 Sept. 1990 to municipal tip	Signature of store manager; date
2	Etc.						

waste treatment plant being constructed, it may be necessary to provide for a separate storage facility.

Temporary storage of untreated/unconditioned waste can on occasion be based on a compromise between the rooms in existing facilities and the construction of a separate building. The use of converted marine shipping International Organization for Standardization (ISO) standard containers as a storage facility for untreated/unconditioned waste has been found to offer a simple solution to such storage requirements [28]. ISO containers have the advantage that they are low cost, readily available, lockable, stackable and designed to withstand severe weather and water ingress from normal precipitation.

If a treatment and conditioning process cannot be installed to avoid the need for storage capacity in a separate building, the design features should be extended to include the following.

- The radioactive waste solids should be stored tidily and placed in drums, bins, racks, pallets or skids suitably planned for minimum handling; this minimizes the risk of the spread of contamination. Aisles should be at least one metre wider than the widest loaded device or vehicle, and account should be made of vehicle turning circles; this minimizes the risk of damaging, toppling or waste containers breaking open when moving through the aisles.
- Shielding should be provided so that the radiation dose rate at any accessible position outside the store does not exceed locally prescribed levels, which are typically of the order of 0.7 mSv/h. Data for shielding from gamma radiation by various materials are provided in Ref. [32]. Shielding for radioactive substances should take account of scattered radiation and source distribution.
- Storage of flammable or toxic liquids or solids should be in a separate area of the building provided with fire resistant storage cabinets and spark resistant lighting. Fire fighting equipment and a fire detection system will also be required.
- Care should be taken if there is a regular turnaround of particular types of waste package; arrangements should be made for a first in, first out receipt/dispatch system to prevent the potential for inadvertently storing some packages for very long periods or, more importantly, not storing some for long enough.
- Storage capacity should be adequate to house the expected waste throughput.
- Access must be designed to be secure, with possible automatic restriction to authorized personnel only. Personal and vehicle radiation monitoring equipment should be installed at exit points.
- The store design should take adequate account of the risk of accidents of both internal or external origin, such as flooding, gales or other severe weather, depending on the location.

5.4.2. Additional design features for liquid waste storage

Collection and storage of radioactive liquid waste should involve the use of approved containers for small quantities of liquid waste and tanks for larger amounts, with provision made for:

- Operational control,
- Collection and interim storage before treatment of a batch,
- Activity decay storage,
- Monitoring.

For obvious safety reasons liquid wastes requiring transfer from a container should not be poured. The design of the installation should include suitable liquid transfer piping and equipment such as leak proof pumps.

Waste in a particular store should be selected for chemical compatibility and suitability for long term retention. Consideration should be given to the provision of a ventilation system together with, if necessary, air monitoring of the storage building. If local climatic conditions are severe this may need to include forced circulation, with heating or cooling and conditioning of the inlet air as appropriate, to avoid extreme temperatures or high humidity conditions.

Small quantities of liquid waste should be absorbed in a suitable material, such as sawdust, before storage. When more active liquid waste is stored it should often be placed in a secondary container or, when small volumes are involved, on a tray large enough to contain the liquid if the primary container starts leaking during storage. Small volumes of organic scintillant should be accumulated in small vials and tubes bulked in hermetically sealed polypropylene containers, with the overall liquid volume restricted to either 1 or 5 L per container (for scintillants with flash points of 21°C or 150°C, respectively).

The design of bulk liquid storage systems for centralized waste treatment plants is evaluated in detail in another IAEA report [1], but the following factors must be taken into account:

- The volumetric and activity inventory and the nature of the liquids to be stored (e.g. corrosive, aqueous or organic);
- The construction constraints, materials and fabrication standards;
- The shielding safety and containment requirements;
- The accessibility for maintenance and remedial action;
- The availability of sampling systems.

Agitation and homogenization of the contents are frequently required and may be achieved by recirculation using a discharge pump, although stirrers or other agitators may be used.

Primary containment may be provided by the storage vessels and secondary containment by the storage cell or structure (for low level waste that is epoxy painted or lined, concrete or fired brick cells may be adequate). Level gauges and alarms must be considered. For any alpha active liquids, a secondary containment may be provided by well constructed gloveboxes. Any leak from a storage tank and its associated piping and fittings needs to be detected and the leak retained by local containment. Sump tanks and transfer devices may be necessary.

Store buildings and their internal surfaces and contents should be constructed with a smooth and impervious finish to allow effective decontamination.

Under certain conditions, waste may generate flammable gases owing to radiolysis or chemical reactions. Depending on the probability of this happening and its probable severity, there may hence be a requirement for the installation of instrumentation systems to detect the buildup of flammable gases, and inert gas or other fire suppression systems. Such systems must be designed to prevent a discharge while people could be in the area, since the gases may cause asphyxiation.

5.5. OPERATING PROCEDURES

5.5.1. Receipt phase

The waste acceptance criteria issued to the producer needs to identify the information that the store manager requires to permit acceptance of a waste package into the store. Once completed by the waste consignor, the store manager should examine the information to confirm that the waste is acceptable for storage; for example, he or she should check that the correct packaging standard is used and that radiation levels are within acceptable limits. If the waste is unacceptable, the details need to be recorded and the documents returned to the consignor with an explanation or request for further information.

On acceptance, the equipment required for transfering the waste (e.g. a forklift truck) to the store should be selected and the store operator should prepare the appropriate documentation required to store the waste. At the store a suitable location for the waste should be identified and the location details recorded. The information provided by the consignor and the storage location of the package should be filed in the store’s central records.

The operator of the storage facility should be trained in the appropriate methods of radiological protection and monitoring, and in the use of the safety equipment necessary for handling any ‘special precaution’ waste packages.

5.5.2. Storage phase

The store manager should be responsible for the waste in the facility and for the maintenance of adequate conditions to allow its satisfactory continued storage, including:

- —Adequate environmental conditions to avoid waste packages deteriorating;
- — Sufficient storage space for future arisings of waste as anticipated by the waste consignors;
- — Correct and appropriate radiological protection procedures to ensure exposure to workers and the public is kept ALARA, and that there is no contamination of the store or the waste packages.

The records of the store contents should be kept up to date, and there should be periodic checking of the store contents against the records. For decay stored waste these records should include the period of storage required and the date on which the waste may be dispatched from the store for disposal.

An audit should be carried out at suitable intervals (e.g. quarterly) by the person responsible for the store to account for each waste package that should be present. Radiation and contamination surveys should be undertaken to ensure that contamination has not occurred. The frequency of the surveys should depend upon the use, quantity and form of the substances; monthly surveys should suffice for a typical store. It is especially important to ensure that appropriate monitoring instruments are used. Some of the commonly used radionuclides emit only low energy radiation not detected efficiently by Geiger–Müller tube equipment; thin window instruments or scintillator detectors may be required. Collection of smear samples with counting in a low radiation background area is required when the gamma dose rates from stored waste exceed about 10 μSv/h.

5.5.3. Dispatch phase

Following the receipt of a request to retrieve a package from storage, the store manager should obtain the details of the particular waste package from the store's records and pass them to the appropriate party. If the details are in order, the package should be accepted for removal from storage. Once the store manager has authorized the release of the waste package, the package should be retrieved from the store and taken to the dispatch area. Here, the package should be monitored for radiation levels before it is released. If the waste package is due for transport from the facility site, the details of the package should be transferred to the transportation records and the waste packaged for transport as appropriate under established standards [29]. The package's storage records should be amended to record the date of dispatch and the receiving party. Any documentation required at the final disposal location should be appropriately completed and checked at the time of the dispatch of the waste.

6. TREATMENT OF AQUEOUS WASTE

6.1. GENERAL CONSIDERATIONS

While it is expected that most low level aqueous waste may be discharged to the environment, either directly or after a suitable decay period, a portion of the waste may need to be treated. The treatment process selected should be based on conventional chemical treatment principles, but the individual characteristics and sources of the waste must be considered. Failure to account for the chemical and biological nature of aqueous waste may result in inadequate treatment and/or conditioning and could even damage the waste processing facilities. Detailed descriptions of the various waste properties that are important for different treatment processes may be found in Refs [3, 33–36].

There are essentially two strategies for medical radioactive waste management that may be employed, dependent upon the facilities and the extent of use of radionuclides within a country:

- An on-site waste management strategy,
- A combination of an on-site and a centralized waste management strategy.

The latter may be appropriate especially in the cases of countries that produce a significant amount of waste containing long lived radionuclides. A centralized strategy is recommended for most long lived radionuclides as it is a cost effective way of treating long lived biomedical radioactive waste contaminated with hazardous chemicals. An on-site strategy would be advantageous for the vast majority of short lived radionuclides used in medicine. In such cases the necessary expertise for waste treatment should be developed within the institutions using the radionuclides, possibly by the project managers or clinicians themselves, or their designated subordinates. In either strategy control by the regulatory body is required, which must be maintained.

Low level aqueous waste appears to be the most straightforward to manage, as much of the extensive existing knowledge of normal water purification processes may be applied to this kind of radioactive waste. However, there can be some problems when using these water treatment processes to meet the specialized requirements of radioactive waste management.

The most obvious problem is the potential for the uncontrolled release of liquids, with the creation of extensive contamination, and therefore every effort must be made to avoid leaks, spills or other unplanned releases. The integrity of containers is especially important when aqueous waste is stored for decay. The management of corrosive aqueous waste requires that the collection, storage and treatment facilities can withstand prolonged exposure to this type of waste, otherwise it must be conditioned directly without any prior treatment.

6.2. SELECTION OF TREATMENT PROCESSES

The selection of a liquid waste treatment system involves making decisions on a number of factors. These can be grouped into five main categories:

— Characterization and segregation of liquid waste,
— Discharge requirements for decontaminated liquors,
— Available technologies and their costs,
— Conditioning of the concentrates resulting from the treatment,
— Storage and disposal of the conditioned concentrates.

The waste streams that are presented for treatment in a waste processing facility usually have a range of components and may not be fully characterized with respect to chemical composition. They may contain organic compounds, oxidizing agents and suspended solids.

The processes available for treating liquid radioactive waste fall generally into three main categories: ion exchange/sorption, chemical precipitation and evaporation. Other processes, such as ultrafiltration/reverse osmosis (UF/RO) and incineration, are used in countries with small or developing nuclear programmes, but not extensively owing to their high capital and operating costs. Table XVII shows the main features of the three basic treatment processes as applied at nuclear fuel cycle facilities.

To a large extent, the selection of a primary treatment process for liquid waste depends upon its radiological and physicochemical properties and the quantity of arisings. It is therefore important to know these properties, not only those predicted by the plant’s design characteristics but also those that result from the actual operating conditions in a plant.

6.3. SOLID/LIQUID SEPARATION

Liquids containing suspended matter must be treated to remove the particulate. This can occur either before primary treatment (such as prior to ion exchange) or after

TABLE XVII. MAIN FEATURES OF THE THREE BASIC TREATMENT PROCESSES

	Chemical precipitation	Ion exchange/sorption	Evaporation
Liquid radiation waste characteristics	Not sensitive to highly salt laden solutions Possible negative effects when oils, detergents and complexing agents are present	Suitable for: — Low suspended solids content — Low salt content — Absence of non-ionic active species	Low detergent content required (owing to foaming problems) Not suitable for volatile radionuclides such as tritium
Decontamination factor (DF)	10–100 (β/γ), 1000 (α), exceptionally >1000 (α)	10 to 10 000, average 100 to 1000	10 000–100 000
Volume reduction factor	10–100 (wet sludge), 200–10 000 (dried solids)	500 to 10 000	Depends on the salt content in the solution
Specificity	Can be tailored to a wide variety of species	Can be tailored to a wide variety of species	Not species specific, but can be tailored for various chemical solvents
Conventional combination with other processes	Possible with evaporation and ultrafiltration	Possible with evaporation	Condensate can be subsequently treated by ion exchange
Process drawbacks	Volume of flocs may be important Dewatering system needed for sludges Chemical hazards associated with reagents	Limited radiation stability Limited heat resistance	Sensitive to scaling, foaming, salt precipitation and corrosion
Application types	Concentration of active species	Demineralization/decontamination of effluent when salt content <1 g/L	Concentration of the solution (active and non-active species)

TABLE XVII. (cont.)

	Chemical precipitation	Ion exchange/sorption	Evaporation
Scope of application	Utility liquid waste from nuclear power plants Low and intermediate level streams in reprocessing operations Nuclear research centres’ liquid waste	Maintenance of pond water quality Water conditioning in reactor circuits Various treatments in reprocessing operations Post-treatment for all other operations	Primary coolant cleanup Utility liquid waste from nuclear power plants Various uses in reprocessing operations
Maintenance	Possible blockage of feed lines and corrosion	Possible blockage of ion exchange beds	Possible foaming, scaling and salt precipitation problems, corrosion
Cost	Relatively low cost	Relatively expensive, mainly for synthetic ion exchangers	Expensive (high energy consumption)

(such as to remove the precipitate/sludge produced in a chemical precipitation process). Various possibilities for treatment include sedimentation and decantation, filtration or centrifugation. For treatments of up to 100 m^3/a, the simple sedimentation and decantation technique is usually the most suitable. Laboratory work may be required to determine the optimum settling and separation conditions for specific waste streams.

6.3.1. Sedimentation

The purpose of sedimentation is to ensure the settling by gravity of suspended solids contained in a liquid and to clear the carrying liquid as much as possible. For chemical precipitation processes the efficiency of this separation is the controlling element of the whole precipitation–flocculation–sedimentation sequence. In fact, because radioactivity concentrates essentially within the sludge to be settled, the traces of sludge swept along will have a direct effect on the decontamination obtained.

Efficient phase separation generally uses a series of conical or sloping bottom tanks with an overflow line for decanted clear liquid and a bottom discharge for the thickened sludge. The process is generally performed as a semi-continuous operation, with periodic shutdowns to remove the accumulated sludge from the tank bottom.

6.3.2. Filtration

Filtration equipment is used to separate fine particulates that will not settle out in a reasonable length of time from a supernatant fluid. It can also be used to pretreat effluent waste by removing miscellaneous debris, and to polish the supernatant liquid as a final processing step.

Various filtration methods are used.

- Natural filtration, using gravity alone in a vertical bed (sand) filter. The dried sludge is removed manually. This method requires large, well formed filtration surfaces. Manual handling of the sludge limits its maximum allowable radioactivity.
- Pressure filtration. By use of a tank and leaf filter, cakes are formed under 2 to 3 kg/cm^2 pressure and dried by a compressed air flow. This flow, when reversed, allows easy removal of the cakes.
- Vertical candle filters, with removal of precoat and cake by compressed air. The residual humidity of the cakes is very low. However, one disadvantage is the risk presented by the use of pressure, which may spread contamination if a leak occurs.
- Vacuum filtration is the most frequently used technique. Generally, precoat type vacuum drum filters are used. The filter assembly is compact, hence easily

protected, and the use of a vacuum improves safety. The residual moisture content of the cakes may reach 40 to 50%.

- Disposable cartridge filters. Similarly to pressure and candle filtration, liquid can be pumped through a filter vessel containing disposable filter cartridges. The recovered particulate is disposed of with the filter elements. This method is particularly suited to small volumes of liquid, since the equipment is simple to operate and is widely available in a variety of sizes, materials and filter ratings.
- An ultrafiltration system is capable of handling a wide range of feeds with solids concentrations from less than 5 mg/L up to over 10 000 mg/L, and particle sizes from much less than 1 μm to over 50 μm. An ultrafiltration plant can be operated continuously with a steady bleed-off of the concentrated liquid sludge. Very high particulate concentrations (over 30% solids) can be obtained.

Typical disposable type cartridge filters are shown in Figs 3(a) and 3(b).

6.3.3. Centrifugation and hydrocyclone techniques

Centrifugation and hydrocyclone devices use centrifugal forces often thousands of times greater than gravity. They may be effective methods for separating liquid and solid streams, and can be more economical and much smaller than gravity operated settling devices.

Centrifugation appears to be applicable only to precipitates that do not show thixotropy, which therefore excludes a number of colloidal suspensions. The difficulties in using these high speed, complex devices in a radioactive environment are likely to outweigh the advantages for treating the effluents considered in this report.

A hydrocyclone is not normally suitable when:

- Solids of less than 5 μm are to be removed,
- The liquid in the slurry is of a high viscosity,
- There is an insufficient specific gravity differential between the liquid and the solid fractions.

6.4. CHEMICAL PRECIPITATION

6.4.1. General principles

Chemical precipitation processes are well established methods for removing radioactivity from low and intermediate level liquid wastes and are in regular use at fuel reprocessing facilities, research establishments and at several power stations. A

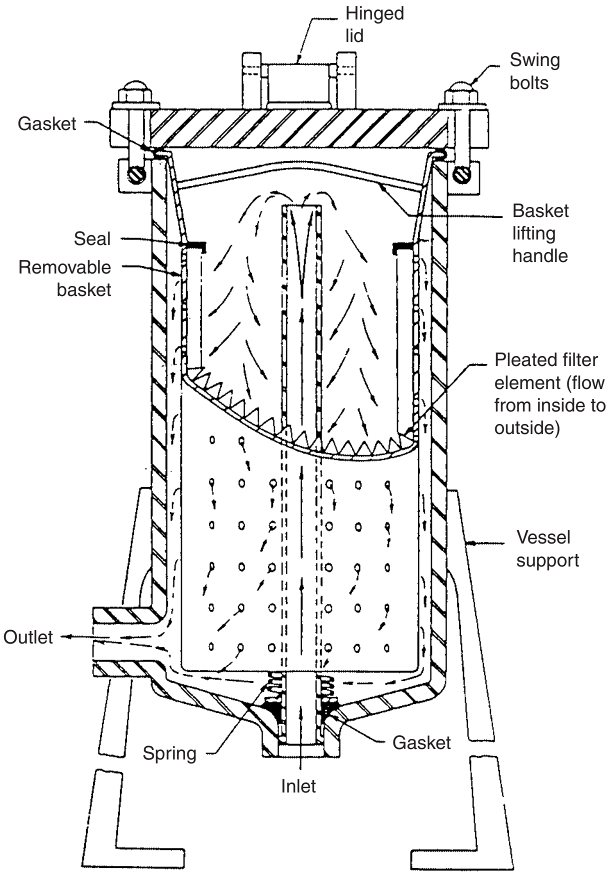


FIG. 3(a). Disposable cartridge filter, with the liquid flow from the outside to the inside of the element. Figure first published in Radioactive Waste Technology (Moghissi, A., Godbee, H.W., Hobart, S.A., Eds), ASME Press, New York (1986).

wide range of different precipitants are now in use (e.g. metal hydroxides, oxalates and phosphates) [33]. Often, small quantities of selected absorbers are added during a floc process to improve or provide decontamination for specific radionuclides [36].

The objective of a chemical precipitation process is to use an insoluble, finely divided solid material to remove radionuclides from a liquid waste. The insoluble material or floc is generally, but not necessarily, formed in situ in the waste stream as a result of a chemical reaction. The majority of precipitation methods use metal hydroxide flocs under neutral or alkaline conditions to remove the radionuclides. In these processes a number of the radionuclides are extensively hydrolysed and are

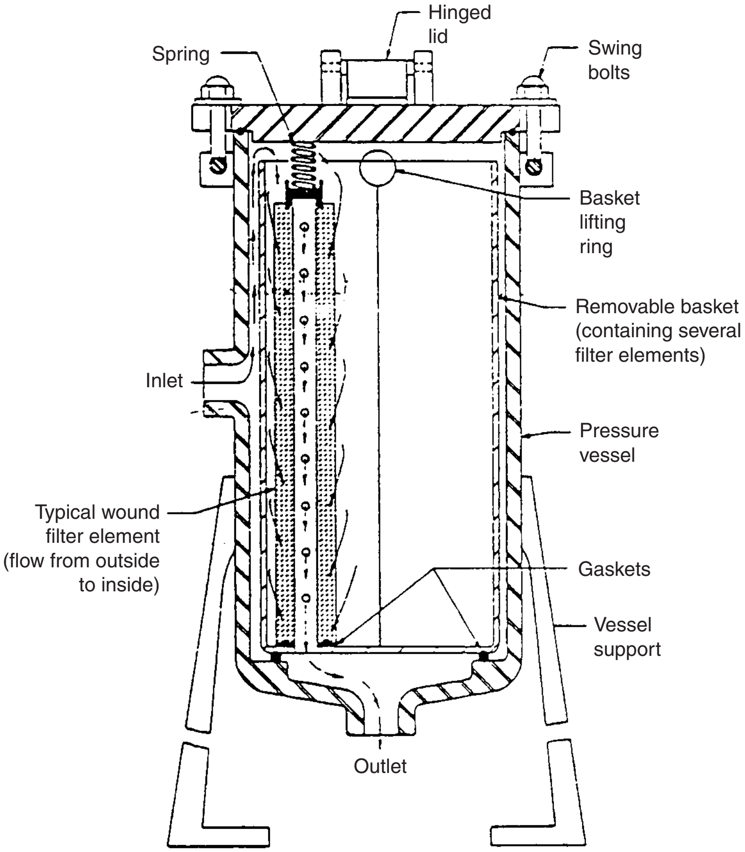


FIG. 3(b). Disposable cartridge filter, with the liquid flow from the inside to the outside of the element. Figure first published in Radioactive Waste Technology (Moghissi, A., Godbee, H.W., Hobart, S.A., Eds), ASME Press, New York (1986).

likely to be either co-precipitated or sorbed on to a floc. Generally, radionuclides are removed from the solution by one or more of the following mechanisms.

- Co-precipitation or isomorphous precipitation with the carrier, where the radionuclide precipitates under the conditions of the process and is subsequently swept out of the solution by the bulk (or scavenging) precipitate, or where the radionuclide is incorporated into the crystal structure of an analogous precipitate (e.g. radiostrontium removal by barium sulphate precipitate);

- Removal of radionuclides already sorbed on to particulates present in the waste effluent, which are separated from the solution;
- Adsorption on to the floc or on added absorbers, for example by ion exchange, chemisorption or physical adsorption.

Precipitation normally involves four main stages:

- The addition of reagents and/or adjustment of pH to form the precipitate,
- Flocculation,
- Sedimentation,
- Solid/liquid separation.

Vigorous agitation is applied during the first stage of the process to ensure rapid mixing of the added reagents and to disperse the precipitant in the waste. The length of time for the initial mixing is a compromise: long times tend to favour increased sorption of radionuclides, but can also cause the formation of colloidal suspensions that cannot subsequently be flocculated. Laboratory tests using real samples of the radioactive waste to be treated are necessary to establish the correct operating conditions.

Flocculation is usually achieved by slowly stirring the mixture. This helps the particles of precipitates to agglomerate into large particles that will settle or can be removed by a separation process such as filtration.

Precipitation processes are particularly suitable for treating large volumes of liquid effluents containing relatively low concentrations of active species. They are fairly versatile and may be used to treat a wide variety of different waste streams, including those containing large amounts of particulates and high concentrations of inactive salts. The processes normally use readily available chemical reagents and are therefore relatively low cost when compared to some alternative processes, for example evaporation, that are 20 to 50 times more expensive.

For the following reasons, chemical precipitation can also be used for waste treatment in countries with small to medium scale nuclear programmes:

- There are relatively low investment and operational costs;
- It has an ability to handle a large variety of radionuclides as well as non-radioactive salts in solution and solid matter in suspension;
- The treatment procedures are based on well proven, conventional plant and equipment;
- It is relatively easy to change or adjust the chemical precipitants, at least in batch processes, in order to accommodate changes in the composition of the liquid feed;

- The process allows for the separation of activity from inactive solutes, which may have a larger bulk.

The waste volume reduction and DFs achieved with a precipitation process are dependent on the method of solid/liquid separation used. Gravitational settling is usually rather slow, so the resultant volume of floc, and hence overall DF, depends on the settling time. The physical nature of some flocs (e.g. gelatinous metal hydroxide flocs) limit the extent to which they can settle under gravity. In these cases secondary processes are necessary to dewater the floc and make it suitable for subsequent treatment, conditioning or storage/disposal.

The decontamination achieved by a floc process also depends on the particular precipitate used, the chemistry of the radionuclide concerned and the degree of separation of the precipitate from the liquid. It may also be affected by the presence of other components of the waste stream, such as complexants, trace organics or particulates. It should be noted that since a chemical precipitation process involves the addition of precipitants or precipitate forming reagents, some of these may raise the level of toxic material in the treated effluent to above the local discharge authorization level. The care and handling of these reagents may also be regulated from a chemical safety standpoint.

For some treatments it may be necessary to include a stage to remove entrained effluent from the sludge; this will be particularly necessary when the effluent contains high levels of inactive salts or ions known to interfere in a subsequent immobilization process: for example, a high ammonium ion concentration cannot be tolerated in cementation processes. A washing process may affect both the floc and the adsorbed radionuclides. The ionic strength of the aqueous phase, and sometimes the pH, changes during washing, which may lead to resolubilization of the radionuclides, with the consequent generation of a new radioactive waste. Reduction in ionic strength of the aqueous phase associated with the floc may also lead to peptization or the formation of colloids of the precipitated material, which, in turn, reduces the efficiency of the solid–liquid separation stage, except possibly in the case of ultrafiltration.

6.4.2. Pretreatment

A pretreatment stage is especially important in the case of the treatment of liquid waste by chemical precipitation. In many cases pretreatment processes may be used prior to the formation of a precipitate in order to improve the decontamination achieved by the precipitation stage. These processes may be carried out to oxidize organic contaminants, decompose complexed species or residual complexing agents, alter the valency state of elements or adjust the ionic species in solution to those with a greater affinity for the precipitate.

Some waste streams may require physical pretreatment, such as coarse filtering and oil/solvent removal, prior to chemical treatment. For example, floor drain waste may contain general debris that could damage pumps, clog pipes or otherwise interfere with subsequent treatment steps.

When considering pH adjustment, oxidation or reduction processes for the pretreatment of a radioactive waste stream, it must be appreciated that a particular treatment may produce both desirable and undesirable effects. For example, the use of a reducing agent may often improve decontamination for a particular metal in the precipitation stage but may have an adverse effect on the removal of other radionuclides by converting them to a lower or more soluble valency state.

6.4.2.1. pH adjustment

Adjustment of the pH can be used to modify the ionic species present in the waste stream. This may influence the choice of precipitants and the operating conditions used in the treatment process.

The adjustment of solution pH can sometimes be advantageously employed in the treatment of waste containing metal ion complexes, in order to form an undissociated acid or base. For example, the precipitative removal of metals from EDTA complexes using calcium hydroxide appears in some cases to be improved by first lowering the pH to a value, for example 1 to 2, where the complex dissociates and free ligand acid is formed, and then raising the pH to a high value, such as 12, to gain maximum advantage from the competitive mass action effects of OH^- and Ca^{2+}. However, this treatment does not remove the complexing agent and so there is the possibility of further problems downstream if other waste streams are blended.

Complex formation is much more of a problem in waste treatment than is often realized. Inadequate stream segregation prior to treatment may create serious problems in plant performance. There are two ways of circumventing the problem (apart from avoiding the use of complexing agents); one is to isolate the stream for a special treatment, such as the use of a technique to recover the complexing agent for reuse, the other is chemical destruction of the complexing reagent, which generally involves oxidative or reductive attack.

6.4.2.2. Chemical oxidation

Chemical oxidation is used in liquid waste treatments to reduce odour, decolorize, destroy organic matter to improve precipitation and flocculation, and oxidize ions such as iron and manganese to a higher valence state and thereby improve the removal of these elements by the precipitation treatment.

Some common oxidants and their applications are discussed below.

- *Chlorine* is a powerful oxidant and, like oxygen, can support combustion, thus presenting a potential fire risk. Sodium hypochlorite is a more acceptable form in which to store and dose chlorine. In addition to the destruction of bacteria and algae, and oxidation of many chemical compounds, the addition of chlorine or hypochlorite has a chemical action that can clarify some effluents by decolorization and deodorization through bleaching the organic matter. It is often advantageous to leave a small residual free chlorine content in the treated effluent to prevent the further growth of bio-organisms.
- *Ozone* is a very efficient sterilizing and oxidizing agent that features several advantages over chlorination. In particular, it does not leave prejudicial decomposition products and allows the destruction of complexing and chelating agents. A number of organic compounds can be oxidized to carbon dioxide and water using ozone, but often only partial degradation occurs. Metal–EDTA complexes appear to be more readily broken down (by an order of magnitude) than EDTA alone. Unfortunately, most of the advantages of ozone are to some extent negated by the relatively high cost of ozone generating equipment and the inefficiencies associated with the low solubility of the gas in water.
- *Hydrogen peroxide* will oxidize many organic substances, particularly when there are unsaturated carbon bonds where attack may take place. The oxidation is often enhanced by the addition of a transition metal ion for use as a catalyst. This catalytic oxidation process has been shown to oxidize EDTA present in solution as metal–EDTA, but further work is necessary to optimize the process. Hydrogen peroxide can be used to oxidize most sulphur-containing compounds, nitrites and hydrazine, and has the advantage of not adding to the dissolved solids concentration.
- *Potassium permanganate* is a powerful oxidizing agent and rapidly oxidizes Fe^{2+}, Mn^{2+}, sulphides and many organic substances. In the pH range commonly encountered in waste treatment (pH 3 to 11) MnO_2 is formed, which is known to be a cation absorber.

6.4.2.3. Chemical reduction

Reduction reactions are employed in waste treatments to convert a pollutant to a solid form, such as in the reductive recovery of metals or precipitation of an insoluble material.

Common reductants and their applications are discussed below.

- *Sodium dithionite* ($Na_2S_2O_4$). The potential for dithionite reduction in an alkaline solution (+1.12 V) suggests that the reagent should be capable of reducing several types of metal ions to the metal. In practice, the metal when formed may be in a colloidal condition and so requires special treatment for separation. The reduction procedure may be useful when metal ions are bound with complexing agents, which renders normal pH adjustment for precipitation of the hydrous oxide inadequate for a full treatment. In alkaline systems the rate of reduction may be slow when metal ions are complexed. Lowering the pH to dissociate the complexes may be necessary, but at lower pH values the reducing power of dithionite is less, so a compromise has to be adopted.

- *Ferrous ion* is a well known reducing agent and is an intermediate reductant in terms of the more widely used reagents. It reduces Cr(VI) to Cr(III), but in solutions with pH > 2 the ferric ion resulting from the reduction stage precipitates, which may be an undesirable addition to the solids produced in the precipitation stage of the process.
- *Hydrogen peroxide* (H_2O_2), although normally considered an oxidizing agent is also a reducing agent. It reduces Cr(VI) compounds providing the pH is slightly alkaline. Silver complexed with thiosulphate, as in photographic fixing solutions, can be precipitated as a silver–silver oxide sludge.

6.4.3. Specific chemical reaction processes

Several chemical processes that operate on the basis of a single or specific chemical reaction to form precipitates are described below. The pH of operation and the expected DFs for some simple processes are summarized in Table XVIII.

Many of these processes have been widely used in the past for treating low and intermediate level aqueous radioactive waste. Advanced treatment processes now in use, or being developed, often combine these simple processes with other processing stages.

6.4.3.1. General precipitation processes

A few precipitation processes are widely used; these basic treatments have shown efficient decontamination for more than one radionuclide and can be considered as general treatments.

The most commonly used simple precipitation processes are:

- The lime–soda process,
- Phosphate precipitation,
- Hydroxide processes,
- Oxalate precipitation.

The lime–soda process. This process removes ‘hardness’ from water and produces a precipitate of calcium carbonate:

TABLE XVIII. SIMPLE CHEMICAL PROCESS TREATMENTS

Radio-nuclide	Process	pH	Expected DF
Pu, Am	Hydroxides (especially ferric)	7–12	>1000
	Oxalates	1	
Cr	Ferrous hydroxide	≥8.5	>100
Mn	Manganese hydroxide, manganese dioxide	≥8.5	>100
Co, Fe	Ferrous or ferric hydroxides	≥8.5	>100
Sr	Ferrous hydroxides	7–13	pH dependent
	Calcium or iron phosphate	>11	>100
	Calcium carbonate	10.5	>100
	Manganese dioxide	>11	>100
	Barium sulphate	≥8.5	>100
	Polyantimonic acid	≈1	>100
Zr, Nb, Ce	Hydroxides (especially ferric)	>8.5	100–1000
Sb	Ferrous hydroxides	5–8.5	5–10
	Titanium hydroxide	5–8.5	10–100
	Polyantimonic acid and manganese dioxide	≈1	20–40
	Diuranate	8.5–10.5	20–30
Ru	Ferrous hydroxide	5–8.5	5–10
	Copper + ferrous hydroxides	8.5	10–25
	Cobalt sulphide	1–8.5	30–150
	Sodium borohydride	8.5	50
Cs	Ferrocyanide	6–10	>100
	Zeolite	7–11	10
	Tetraphenylborate	1–13	100–1000
	Phosphotungstic acid	≈1	>100
	Ammonium phosphomolybdate	0–9.5	>10

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3 + 2H_2O$$
$$Ca(OH)_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaOH$$

This process has been used in the past primarily to remove strontium as an analogue of calcium, but has now been superseded by more efficient processes. However, the simplicity and low cost of the process still makes it attractive for some applications.

Phosphate precipitation. Soluble phosphates, especially tri-sodium phosphate, are added to the waste to form insoluble compounds with other ions.

$$3M^{n+} + nPO_4^{-} \rightarrow M_3(PO_4)_n$$

where M is Fe^{3+}, Al^{3+}, Ca^{2+}, etc., including radioactive strontium. Calcium ions are usually added as a bulk co-precipitant to enhance the removal of other cations. The reaction is complex and some type of hydroxyapatite, whose structure can include strontium ions, is probably formed. The method also achieves good removal of metals, such as uranium, which have insoluble phosphates. In general, the higher the pH of the operation, the better the DF achieved. For strontium a DF of >100 is obtained at pH values >11. However, the removal of caesium by this method is poor.

Currently barium sulphate precipitation, sometimes in combination with other precipitates, is used more often than the phosphate process for strontium removal.

Hydroxide processes. Many metal ions can be hydrolysed to form insoluble hyroxocompounds, a number of which exhibit an affinity for the sorption of other ions.

$$M^{n+} + nOH^{-} \rightarrow M(OH)_n$$

where M is Fe^{3+}, $A1^{3+}$, Ti^{4+}, etc.

Although in conventional water treatment aluminium hydroxide precipitation is widely used, in the practice of radioactive waste management the use of ferric hydroxide precipitation is more common, partly because ferric ions may already be present in some waste streams owing to equipment corrosion. In general, ferric hydroxide floc particles are larger and easier to settle than those of aluminium hydroxide.

Ferric hydroxide forms as a voluminous, gelatinous precipitate, which may be difficult to handle. Conventional filtration is not very effective, so gravity settling is usually favoured for the initial separation. There is also the possibility of carry-over of fine particles of floc suspended in the supernate. Generally, ferric flocs require further dewatering prior to immobilization and the supernates often need to be polished in order to improve decontamination. The physical properties of the floc may be significantly improved by the presence of other precipitates (for example calcium salts). Ferric floc treatment may be affected by the presence in waste streams of other components, such as carbonate ions, or some complexants, for example EDTA and citric acid.

6.4.3.2. Treatment for specific radionuclides

The treatments initially applied to radioactive wastes were those used to purify municipal and industrial wastewater. In some cases, depending on the specific chemical and radiochemical composition of the waste, these treatments do not provide sufficient decontamination from certain radionuclides, and special treatments have therefore been developed; those for strontium and caesium are described as examples below.

Strontium removal. Strontium is generally removed by the general precipitation processes described above. A number of other specific precipitation processes, such as with barium sulphate and hydrous oxides of manganese, titanium and antimony, may be employed when the general treatment processes are not effective (for example in the presence of calcium and magnesium ions).

The removal of strontium by in situ precipitation of barium sulphate occurs by the isomorphous precipitation of the strontium. The removal of strontium increases when increasing the pH value of the stream; at pH8.5 the DF is between 100 and 200. The literature contains many reports presenting data on the sorption of strontium by inorganic sorbents such as polyantimonic acid, hydrous titanium oxide, sodium titanate and manganese dioxide. Recent investigations describe the use of finely divided precipitates of these materials either singly or in combination [36].

Caesium removal. A number of precipitation processes exist for the removal of caesium from aqueous waste streams:

- The use of transition metal ferrocyanides (Cu, Ni, Co);
- The use of phosphotungstates or phosphomolybdates;
- Precipitation of tetraphenylborate.

Transition metal ferrocyanides are those most commonly used and can be precipitated in situ or added as a preformed slurry. Caesium adsorption appears to be affected by ion exchange. Decontamination factors higher than 100 are frequently observed. Different metal ferrocyanides provide maximum decontamination at specific pH values. The most commonly used are copper and nickel ferrocyanides, which are effective over the pH range 2 to 10.5 and in the presence of high salt loadings (>5M Na^+), but DFs decrease with increasing salt content [34, 36].

At pH values greater than 11 decomposition of the transition metal ferrocyanides occurs, yielding the ferrocyanide ion and a precipitate of the transition metal hydroxide.

6.4.3.3. Combined precipitation processes

When the waste stream composition is variable in nature, either in radioactive or non-radioactive content, a single chemical precipitation process may be inadequate.

In order to provide a good decontamination of the liquid waste, a combination of the general or specific treatments previously described is frequently necessary. To achieve the best overall DF for specific radionuclides or for the total activity of the liquid waste, often the final combined chemical process is a compromise between the optimal conditions of each single process.

6.5. ION EXCHANGE/SORPTION

The use of ion exchange procedures in chemical processing, water and wastewater treatments was well developed by the time the technique was first applied in the nuclear industry. Since then much progress has been made in improving the technology, and ion exchange methods have been widely used to remove soluble radionuclides from liquid waste. Recent developments in ion exchange technology and applications are described in other publications, such as Refs [35–37].

The process involves the exchange of ionic species between a liquid solution and a solid matrix containing ionizable polar groups. When exchangers become fully loaded they are removed from service and treated as radioactive waste. Alternatively, many organic ion exchange materials may be regenerated by strong acids or bases, yielding radioactive liquid waste with a high salt and activity content.

Ion exchange media are available in many combinations of natural or synthetic, organic or inorganic materials, and in cation or anion exchange forms. Many media are also available in a variety of physical (e.g. bead or powdered) and chemical forms (e.g. H^+ or Na^+ counter ions). Cation exchangers are used to remove cationic species such as Cs^+ or Sr^{2+}, while anion exchangers remove anionic species such as Cl^-. Highly specific ion exchange media are readily available for radionuclides common in the nuclear industry, such as Cs and Sr, but these are not frequently encountered in non-nuclear power applications.

Ion exchange processes can be operated in batch or continuous modes. In a batch operation a measured amount of media is added to a tank of liquid, stirred and allowed to equilibrate for a specified time. The media can then be filtered from the liquid. This type of operation is suited to small scale, bench top operations. In a continuous operation the media is contained in a vessel and the liquid is pumped through the media under pressure. Separate vessels can be used for cation and anion exchange, or the two media can be combined into a single vessel (termed a ‘mixed bed system’). Typical separate bed and mixed bed ion exchange units are shown in Fig. 4. Further details about the use and operation of ion exchange systems can be found in other publications, such as Ref. [37].

Ion exchange methods have extensive applications in nuclear fuel cycle operations and other activities involving radioactive materials. Examples of these include the cleanup of primary and secondary coolant circuits in nuclear power plants, treating fuel storage pond water at nuclear power and reprocessing plants, cleanup of active drainwater and treating liquid waste arising in radioisotope production and research facilities.

DFs can range between perhaps 10 for simple systems to 10^7 for very sophisticated systems; however, values of 100 to 1000 are relatively common. Generally, the lower DFs are based on gross activity and the higher figures are nearly always for specific radionuclides for which the system has been designed.

The application of ion exchange resins in a small nuclear research centre as a main method for decontaminating radioactive effluents is not recommended. Based on the experience gained from existing ion exchange processes and the more recent results from development studies, the application of ion exchange resins to remove activity from radioactive effluents offers a number of disadvantages:

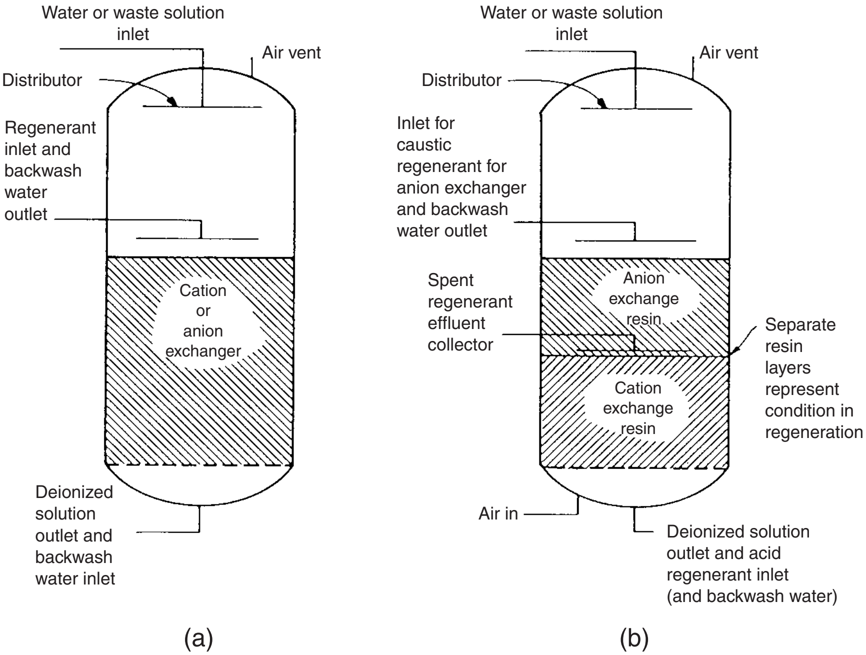


FIG. 4. Schematic diagrams of the (a) separate bed and (b) mixed bed ion exchange systems. Figure first published in Radioactive Waste Technology (Moghissi, A., Godbee, H.W., Hobart, S.A., Eds), ASME Press, New York (1986).

- —The resins show a very low capacity for effluents with high inactive salt contents (>1 g/L);
- — Regeneration gives rise to secondary waste;
- — Non-electrolytes, colloids, suspended and dissolved organics, detergents and complexing agents cause difficulties and reduce the DFs;
- — Only ion specific exchangers can reduce or eliminate most of the above limitations.

6.6. EVAPORATION

Evaporation is a well established process, widely used in the nuclear industry [35]. A typical simple evaporation system is shown in Fig. 5. It is capable of giving high decontaminations and large volume reductions and is currently being used for the treatment of high, intermediate and low level waste effluents. On cost considerations, evaporation is a relatively expensive process and is therefore more attractive

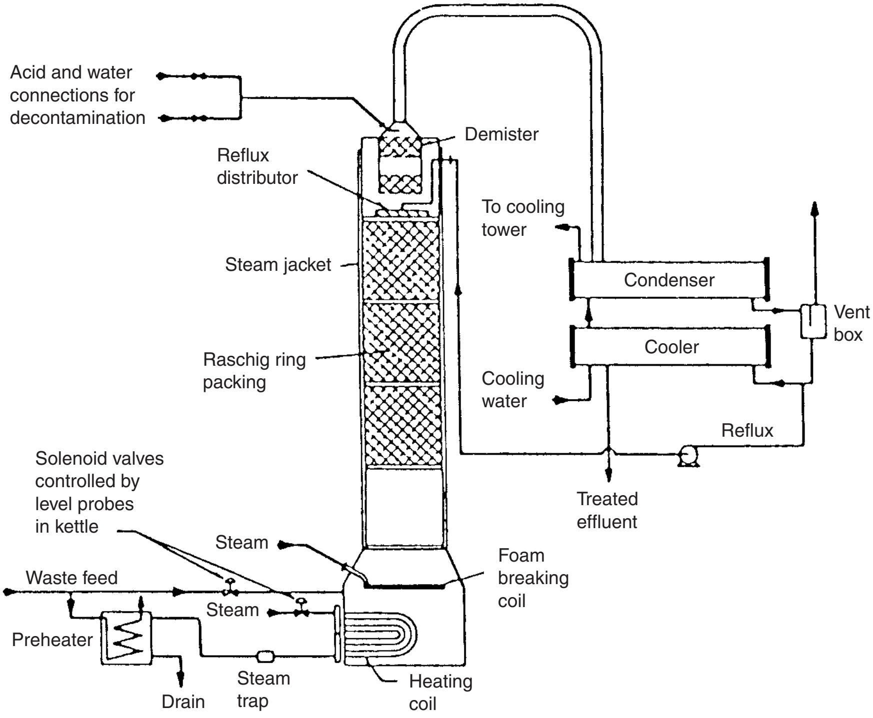


FIG. 5. A typical pot type evaporator.

for the treatment of small volumes of highly active effluents than for the treatment of large volumes of low level waste. It is, however, used for low level waste concentration at some sites with large volumes contaminated with fission and corrosion products.

When compared with other effluent treatment processes, the evaporation process is in principle relatively simple. Essentially, it involves distilling the solvent from a waste effluent, leaving a smaller volume of residue containing both the radionuclides and the inactive salts. In practice, evaporation gives very good decontamination for all non-volatile radionuclides (up to 10^4 in a single stage evaporator) and can result in very large volume reductions provided that the inactive salt content of the stream is relatively low.

The condensate resulting from evaporation is an almost salt free solution of very low activity that may be subsequently polished by ion exchange before it is discharged or recycled. The concentrate containing the radionuclides can either be dried to produce a salt cake or be incorporated into a suitable matrix (e.g. cement) for disposal.

Apart from some obvious advantages, for example its large volume reduction and high DFs, evaporation has some important limitations:

- It is unsuitable for waste effluents containing large concentrations of inactive salts, since the extent of volume reduction is determined by the dissolved solids content;
- It is expensive compared with other treatment processes (e.g. 20 to 50 times more expensive than a floc process) owing to its large energy requirement;
- The problems caused by corrosion, scaling and foam formation may prevent the successful evaporation of some wastes;
- The presence of some organics, for example tributylphosphate (TBP) in nitric acid, can result in explosions during evaporation, and an appropriate pretreatment, such as steam stripping, is required.

All of these problems should be considered as potential limitations of the process. The performance of evaporators is strongly influenced by these factors, therefore it is important that the process designer be extremely knowledgeable about the chemical and physical properties of the waste requiring treatment.

6.7. NEW TECHNOLOGIES

6.7.1. Reverse osmosis

Reverse osmosis (RO) systems are in use for water treatments (such as desalination of sea water to produce potable water), as well as for the treatment of some radioactive liquid waste streams [38]. An RO system is essentially the application of a very fine pore filter capable of removing dissolved solids, ionic species and microbial contamination. Owing to the extremely small pore sizes of the RO membranes, they are highly susceptible to plugging and scaling. Consequently, the feed liquid must be pretreated by ultrafiltration in order to remove as much of the finest particulate as possible.

The RO membrane is formed from thin film polymer sheets with uniform microfine pores. In order to obtain a large surface area, the membranes are formed into tubes or spiral wound on to supports. RO is a cross-flow process, with the liquid flowing parallel to the membrane surface. (In conventional filtration, the liquid flow is perpendicular to the surface of the filter medium.) If the applied differential pressure across the membrane is sufficient to overcome the osmotic pressure of the liquid, clean water permeates from the liquid being treated to the clean side of the membrane, where it can be collected. Since RO systems generally operate at very high pressures (5 to 10 MPa or more), special precautions, such as secondary containment, must be provided in case the system leaks.

An RO plant can be operated continuously and produces two effluent streams: a clean permeate stream (75 to 98% of the original volume) and a concentrated waste stream (2 to 25% of the original volume). The permeate stream is often suitable for direct discharge without further treatment, while the concentrate can be dried by evaporation, treated by chemical precipitation or immobilized directly. The process is best suited to dilute waste streams. The higher the total dissolved salt concentration, the higher the pressure required, and the lower the recovery efficiency of clean water. Efficiency can be improved by adding additional RO stages in series.

RO systems can be costly to install and operate on a large scale. Smaller laboratory scale systems are commercially available for water purification and can be adapted for some radioactive liquid waste treatment applications. In all systems, the membranes can be fouled by many different chemical compounds and must be regularly cleaned. Careful control is also required over the pH and organic concentrations in the feed liquid. In some cases the RO process itself may cause a change in pH sufficient to result in the precipitation of foulants in the pores of the membrane.

7. TREATMENT OF RADIOACTIVE ORGANIC LIQUID

Liquid organic radioactive waste such as oils, scintillation fluids, solvents and miscellaneous biological fluids is generated from the production and use of radioisotopes in nuclear research centres, and in medical and industrial applications. In most cases the volume of this waste is small by comparison with aqueous waste. While most aqueous waste may be discharged to the environment following treatment or decay storage, organic liquids may require more elaborate treatments to remove or destroy chemically or biochemically hazardous components [4].

7.1. PRETREATMENT CONSIDERATIONS

7.1.1. Strategic considerations

Even though the volume of organic liquid waste is small, it is important that effective waste management practices are established, especially in class A, B and C countries, which generally lack the waste management infrastructure associated with a nuclear power programme.

Because of its nature and origin, organic liquid waste may present hazards other than radioactivity. For example, the organic liquid may be chemically hazardous (as in the case of many solvents), biologically infectious (as in the case of some medical waste) or otherwise hazardous (as in the case as some pharmaceuticals). Each of these factors must be considered when planning and implementing a radioactive organic waste management system.

The waste management strategy may require treating the waste by processes such as distillation to concentrate the radioactivity and/or separating the components by evaporating those that are non-active, or by incineration to destroy the organic material. The treated waste may then need to be conditioned to prevent radioactivity from escaping into the environment.

There may be a number of processing options applicable to each of the different waste types. An integrated waste management system that deals with a variety of wastes can be based on a combination of several treatment methods, each optimized for a single waste stream (or limited number of waste streams). Another option could be the selection of a single treatment method that adequately handles a broad range of wastes. The choice of the best approach to use in a given country requires a careful evaluation of a number of factors, including the waste stream characteristics and volumes, local availability and cost of equipment, familiarity with process operation and downstream disposal requirements.

7.1.2. Preliminary waste management steps

Radioactive organic liquid waste should be collected and stored until a sufficient quantity has accumulated to justify its transport to a central radioactive waste management facility. The following steps should be taken to ensure safety during this phase and to avoid later difficulties at the processing stage.

The different waste types should be segregated during waste collection. For example, waste containing short lived radioisotopes should not be mixed with waste containing long lived radioisotopes, liquid scintillation solvents should be kept separate from other solvents, and oils and solvents should be stored in separate containers. Organic liquids should not be mixed with aqueous liquids, since this complicates further treatment for both. Suitable records should be maintained identifying the type of waste in each container, the radioisotopes present and their activity levels.

If the processing facility is off-site it is preferable that the liquid waste be collected and stored in containers suitable for transport, such as steel drums. If on-site storage for decay is practised, the container must be suitable for extended storage. Care should be taken not to use containers that may corrode and leak their contents. Glass containers should be avoided if possible. If glass is used, the containers must be suitably protected against breakage.

Because of the chemically active and flammable nature of organic liquid waste, its collection and storage area should be isolated from other activities and there should be adequate fire protection and ventilation. In extreme cases inert gas, CO_2 or nitrogen blanketing systems may be considered. In cold climates heating may be required to prevent the liquids from freezing and subsequently rupturing their containers. Conversely, in hot climates cooling may be required for storing volatile solvents.

7.1.3. Process selection

A number of treatment processes and technologies are available to treat organic radioactive liquids. Many of these processes treat a variety of wastes and an individual waste stream may be treatable by a variety of methods. An integrated waste management plan should take all of these factors into consideration. It is assumed that the differences in volumes, types and radioisotope content of wastes for different countries or sites will present different requirements, which may influence an individual country or site specific preference for a given process. The potential for solvent recovery and reuse provides a benefit for cost saving and should not be overlooked in the selection process.

Since aqueous and solid radioactive waste volumes greatly exceed those of organic liquid waste, it is likely that priority will be given to their treatment. In some cases processes and equipment selected for the treatment of aqueous and solid waste can be adapted for processing organic liquid waste, and combined processing could be cost effective. For example, small quantities of organic liquid can be readily mixed with solid waste in an incinerator.

Where dedicated equipment for the destruction of organic liquid waste is desired, equipment cost, versatility of the treatment for a number of organic liquid wastes, equipment availability, reliability of operation of the equipment and ease of maintenance of the equipment are all factors to be considered in the selection process.

Some of the processes, such as wet oxidation, acid digestion, electrochemical oxidation and distillation, can be carried out for small batches of waste using simple bench top equipment. For larger waste arisings a dedicated plant may be considered.

Often, substantial advantages can be accrued by selecting a combination of two or more processes, rather than a single process, for treating organic liquid waste. For example, the multiple process approach may allow resource recovery, convert the organic material into an inert form, provide volume reduction or allow processing in equipment designed for solid waste. Figures 6 to 8 suggest some possible process combinations for treating scintillation liquids and miscellaneous solvents, oils and solvent extraction wastes, respectively. Some of the advantages and disadvantages of each combination are also presented. The final selection of the processes to be used will, of course, be based on the national need and/or availability of resources.

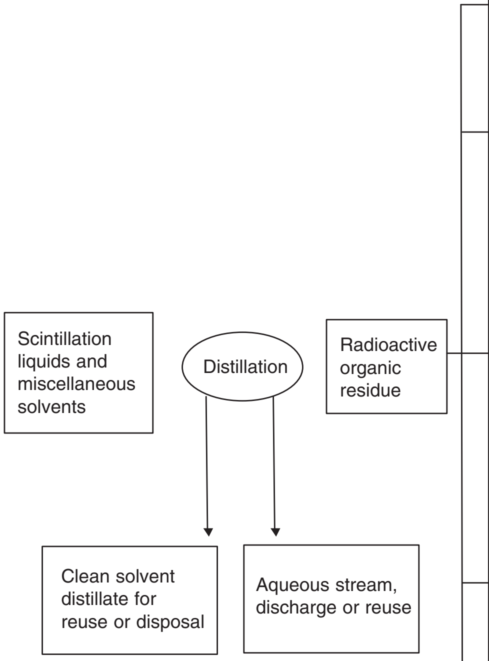
7.2. TREATMENT PROCESSES

7.2.1. Incineration

Incineration is an attractive technique for treating organic liquids because they are readily combustible and high volume reduction factors may be achieved. In principle, the products of complete combustion are the oxides of the elemental constituents, mainly carbon dioxide and water. Other oxides are also formed, depending on the composition of the waste. For example, P_2O_5 and NO_2 are formed from the combustion of TBP and amines, respectively, and these acid gases in combination with water may produce corrosive conditions.

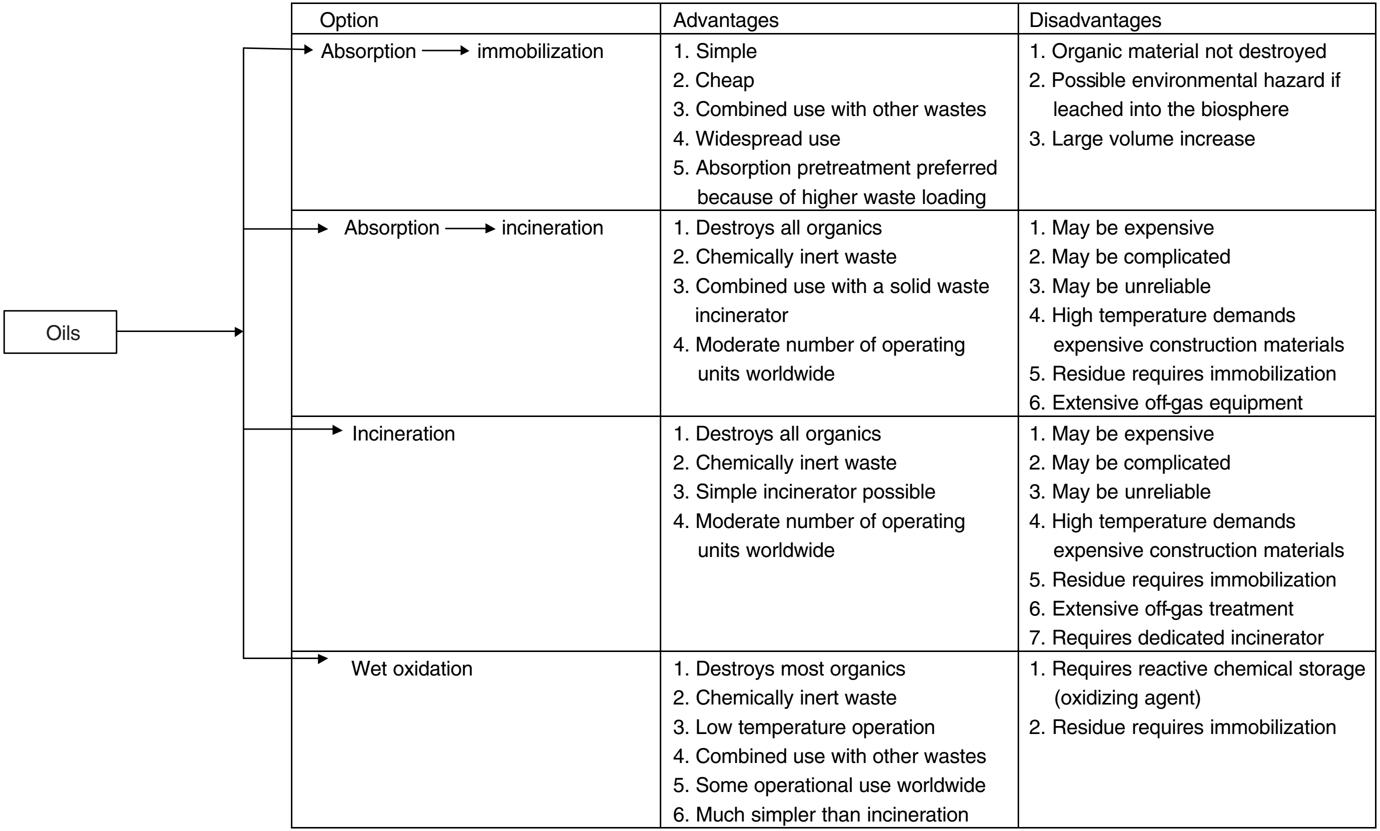
Sulphur and chlorine produce corrosive combustion products (HCl in the case of chlorine), which if present in substantial proportions in the waste can require special means to limit the effects of corrosion on plant equipment. Volatile radionuclides, such as ^{3}He, ^{14}C and iodines, are released with the exhaust gases, which in some cases require further specific off-gas treatments (e.g. scrubbing or filtration). The non-volatile inorganic components of destroyed organic liquid waste tend to remain in the ash.

Throughout the world a variety of incinerator types and concepts have been tried [4, 39–42]. In general, incinerators for low level radioactive waste have proved more successful than those for intermediate level radioactive waste, since they tend to be less demanding to construct, operate and maintain. Incineration is often practised in dual purpose solid and liquid radioactive waste incinerators. For large volumes of liquids these tend to be less successful than dedicated liquid incinerators optimized for the purpose. However, small volumes of organic liquids may be easily handled in most solid waste incinerators. In these incinerators liquid waste, such as scintillation



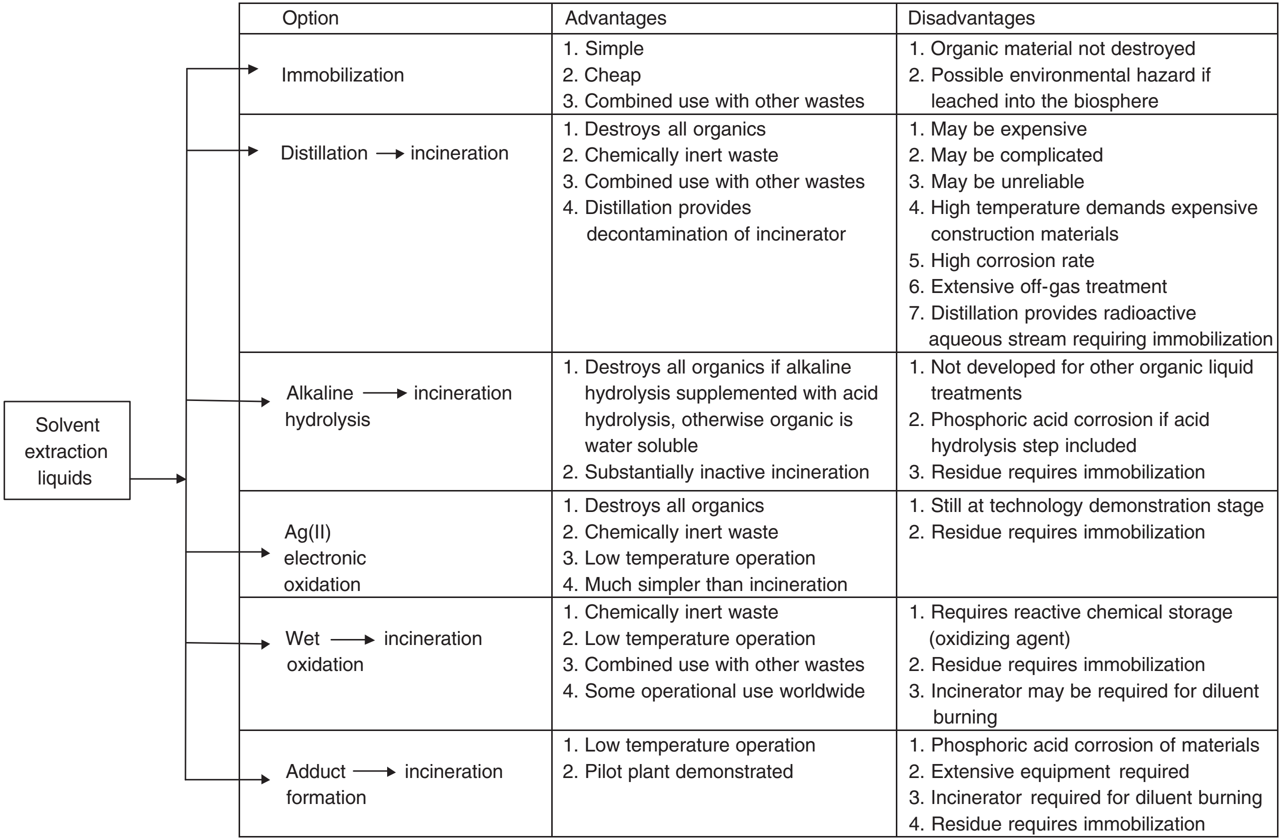
Option	Advantages	Disadvantages
Immobilization	1. Simple 2. Cheap 3. Combined use with other wastes 4. Widespread use	1. Organic material not destroyed 2. Possible environmental hazard if leached into the biosphere
Incineration	1. Destroys all organics 2. Chemically inert waste 3. Combined use with other wastes 4. Moderate number of operating units worldwide	1. May be expensive 2. May be complicated 3. May be unreliable 4. High temperature demands expensive construction materials 5. Residue requires immobilization 6. Extensive off-gas equipment
Wet oxidation	1. Destroys most organics 2. Chemically inert waste 3. Low temperature operation 4. Combined use with other wastes 5. Some operational use worldwide 6. Much simpler than incineration	1. Requires reactive chemical storage (oxidizing agent) 2. Residue requires immobilization
Ag(II) electrochemical oxidation	1. Destroys all organics 2. Chemically inert waste 3. Low temperature operation 4. Much simpler than incineration	1. Still at technology demonstration stage 2. Residue requires immobilization
Acid digestion		1. High temperatures, concentrated nitric and sulphuric acids 2. Extensive off-gas equipment 3. Expensive construction materials 4. Residue requires immobilization 5. Not commercially used

FIG. 6. Process combination options for treating scintillation liquids and miscellaneous solvents.



Option	Advantages	Disadvantages
Absorption → immobilization	1. Simple 2. Cheap 3. Combined use with other wastes 4. Widespread use 5. Absorption pretreatment preferred because of higher waste loading	1. Organic material not destroyed 2. Possible environmental hazard if leached into the biosphere 3. Large volume increase
Absorption → incineration	1. Destroys all organics 2. Chemically inert waste 3. Combined use with a solid waste incinerator 4. Moderate number of operating units worldwide	1. May be expensive 2. May be complicated 3. May be unreliable 4. High temperature demands expensive construction materials 5. Residue requires immobilization 6. Extensive off-gas equipment
Incineration	1. Destroys all organics 2. Chemically inert waste 3. Simple incinerator possible 4. Moderate number of operating units worldwide	1. May be expensive 2. May be complicated 3. May be unreliable 4. High temperature demands expensive construction materials 5. Residue requires immobilization 6. Extensive off-gas treatment 7. Requires dedicated incinerator
Wet oxidation	1. Destroys most organics 2. Chemically inert waste 3. Low temperature operation 4. Combined use with other wastes 5. Some operational use worldwide 6. Much simpler than incineration	1. Requires reactive chemical storage (oxidizing agent) 2. Residue requires immobilization

FIG. 7. Process combination options for treating oils.



Option	Advantages	Disadvantages
Immobilization	1. Simple 2. Cheap 3. Combined use with other wastes	1. Organic material not destroyed 2. Possible environmental hazard if leached into the biosphere
Distillation → incineration	1. Destroys all organics 2. Chemically inert waste 3. Combined use with other wastes 4. Distillation provides decontamination of incinerator	1. May be expensive 2. May be complicated 3. May be unreliable 4. High temperature demands expensive construction materials 5. High corrosion rate 6. Extensive off-gas treatment 7. Distillation provides radioactive aqueous stream requiring immobilization
Alkaline hydrolysis → incineration	1. Destroys all organics if alkaline hydrolysis supplemented with acid hydrolysis, otherwise organic is water soluble 2. Substantially inactive incineration	1. Not developed for other organic liquid treatments 2. Phosphoric acid corrosion if acid hydrolysis step included 3. Residue requires immobilization
Ag(II) electronic oxidation	1. Destroys all organics 2. Chemically inert waste 3. Low temperature operation 4. Much simpler than incineration	1. Still at technology demonstration stage 2. Residue requires immobilization
Wet oxidation → incineration	1. Chemically inert waste 2. Low temperature operation 3. Combined use with other wastes 4. Some operational use worldwide	1. Requires reactive chemical storage (oxidizing agent) 2. Residue requires immobilization 3. Incinerator may be required for diluent burning
Adduct formation → incineration	1. Low temperature operation 2. Pilot plant demonstrated	1. Phosphoric acid corrosion of materials 2. Extensive equipment required 3. Incinerator required for diluent burning 4. Residue requires immobilization

FIG. 8. Process combination options for treating solvent extraction liquids.

fluids in plastic vials, may be packaged in small incinerable containers, such as 5 L plastic or cardboard pails, and batch fed in controlled amounts with solid waste. Other liquids, such as oils and solvents, may also be fed this way, often by mixing with a sorbent, such as sawdust, to convert the liquid into a semisolid.

Solid waste incinerators may be classified as excess air or starved air (pyrolysis) types, but liquid waste incinerators are almost exclusively of the excess air type. High calorific value organic waste and a high demand for oxygen may lead to vigorous turbulent burning conditions, which require filtration to prevent radioactive ash escaping into the environment.

A simple cyclone type incinerator has been developed at the Mound Laboratory in the USA [39]; this consists of a mild steel drum as the main incinerator vessel fitted to a closure in place of the normal drum lid. The closure contains a number of apertures for feed and off-gas pipework, and an ignitor. This simple concept allows the ash to accumulate in the drum, so that the drum and its contents may be removed when appropriate for disposal, and a new drum fitted for subsequent use. Off-gases are treated in a wet scrubbing system with recirculating scrub liquor.

Other common equipment, such as oil fired furnaces, may often be adapted for incinerating organic liquids by providing secondary containment and an off-gas filtering system to control radioactive discharges.

7.2.2. Wet oxidation

Wet oxidation is a technique for breaking down organic materials to carbon dioxide and water in a process analogous to incineration. In the simplest system organic waste is reacted with hydrogen peroxide in the presence of a catalyst at 100°C and the excess water is distilled or evaporated to leave a concentrated inorganic waste containing the radioactivity. The main advantages of the process are low temperatures and conversion to an aqueous waste stream that is easy to treat. Good dispersion of organic waste in the aqueous phase is important. Early applications have been for polar materials, including TBP and organic acid decontamination reagents, but more recently this technique has been developed for the treatment of non-polar materials [5].

The oxidation reaction is exothermic and, once the operating temperature has been reached by, for example, steam preheating, provides sufficient heat input to maintain the reaction temperature and pressure. Control of the reaction rate may be required, however, to prevent too much heat being generated. Owing to the harsh oxidizing conditions present, special alloys may be required for the reaction vessel. The radionuclides are concentrated in the sludge produced in the oxidation reactor. Tritium-containing waste is not treatable by this process.

Small, simple systems may be constructed using laboratory scale equipment. The main parameters to consider are reaction temperature, oxygen availability and time in the reactor. Larger, more complex systems have been constructed in the United Kingdom [43] and in Canada [44].

7.2.3. Electrochemical oxidation

This process offers an alternative oxidation method to incineration and has some parallels with the wet oxidation process [45]. Both processes operate at much lower temperatures than incineration and do not have the problems of off-gas cleanup that are associated with incineration.

Both wet oxidation and the electrochemical oxidation process feature the use of strong oxidizing agents. Whereas the wet oxidation process features the use of hydrogen peroxide, the electrochemical oxidation process uses Ag(II) in a solution of silver nitrate and nitric acid, and involves placing the solution in the anode compartment of an electrochemical cell and passing through a current.

The anode and cathode cells are separated by a semipermeable membrane that allows the passage of the ions carrying the current through the cell but prevents gross mixing of the contents of the compartments. Aqueous Ag(I) is oxidized to Ag(II) electrochemically. In the anolyte the Ag(II) reacts with water to form oxidizing and reactive species such as OH· radicals. These reactive species react with the organics being fed to the anolyte, ultimately oxidizing them to carbon dioxide, some carbon monoxide, water and other inorganic products. Essentially the same operating conditions may be used for a variety of waste types; there is no volatilization of low molecular weight species formed as intermediates during the destruction process, and the process can be readily started and stopped by switching the current on or off.

7.2.4. Acid digestion

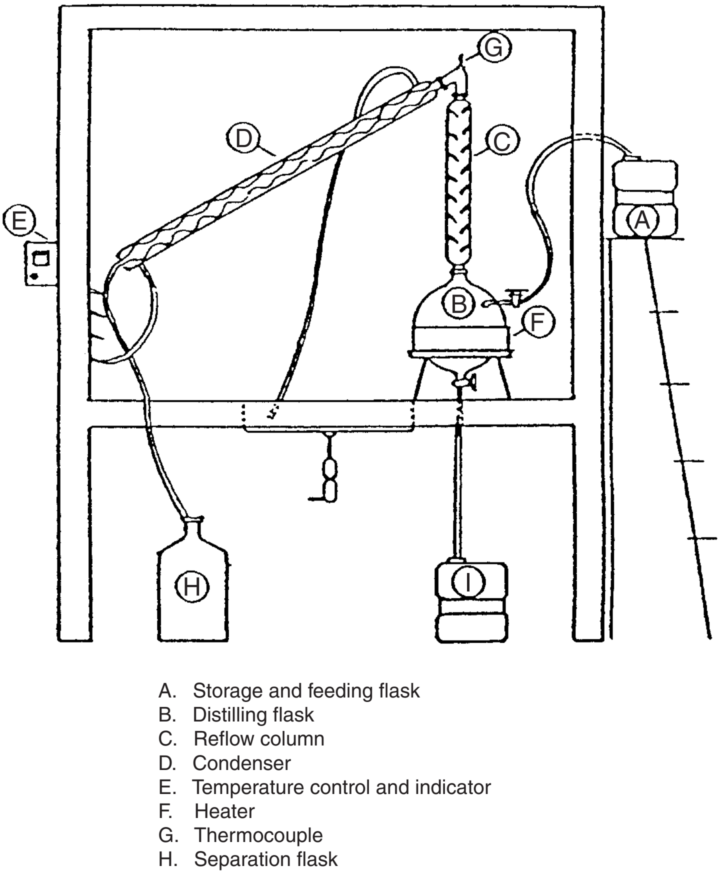
This process has been under development in a number of countries, although only Germany and the USA have any significant experience in the operation of an industrial scale plant. The process requires the use of mixed nitric and sulphuric acids at ~250°C, with a consequent need for expensive corrosion resistant construction materials. Extensive off-gas scrubbing is required as sulphur dioxide and nitrogen dioxide are generated during the process. Some organic liquids, such as hexane and TBP, can be treated effectively, although others, such as paraffins, only partly digest, with the balance being lost from the reaction vessel by distillation. Trichloroethane and toluene do not digest well unless they are well dispersed by atomization.

A major disadvantage of the process is the potential creation of large volumes of highly corrosive secondary waste (strong acids), which may be equally or more difficult to treat than the original organic waste. This may be minimized by neutralization of the waste acid stream with waste caustic (possibly from another process, such as alkaline hydrolysis) and subsequent dilution before release into the environment.

7.2.5. Distillation

Simple distillation as shown in Fig. 9 may be used for pretreating scintillation fluids and miscellaneous solvent waste. Substantial volume reduction is possible as the activity is generally concentrated in the residue. The recovered organic can be recycled as a technical grade solvent or used as a fuel for an incinerator.

Distillation can be practised with conventional readily available equipment; space requirements for the equipment are small. The process is simple and well known, and operators require only limited training. Distillation is cost effective in that valuable solvents can be recovered for some form of reuse. The active residue can be either immobilized or further treated by incineration.



- A. Storage and feeding flask
- B. Distilling flask
- C. Reflow column
- D. Condenser
- E. Temperature control and indicator
- F. Heater
- G. Thermocouple
- H. Separation flask
- I. Waste storage flask

FIG. 9. Distillation apparatus for scintillation solutions.

Distillation equipment can also be used for recovering dry cleaning solvents, which can often be recycled or reused. The resulting sludges can be incinerated or immobilized for storage and disposal.

Vials containing liquid scintillation counter fluids may be uncapped by hand to release the solvent. Alternatively, they can be crushed using specially designed equipment. In either case fire and respiratory protection must be provided owing to the flammable and toxic nature of the solvent.

7.2.6. Phase separation by adduct formation

Phase separation by adduct formation has been investigated as a pretreatment method used prior to the destruction or disposal of TBPs and diluents [46]. This is carried out by contacting contaminated TBPs/diluents with concentrated phosphoric acid at room temperature in conventional solvent extraction equipment such as mixer–settlers or pulsed columns. The TBP is solubilized quantitatively in the phosphoric acid and forms a TBP–acid polar adduct, whose formula is quoted as ranging between $3TBP{\cdot}H_3PO_4{\cdot}6H_2O$ and $TBP{\cdot}4H_3PO_4$. Almost all of the radioactivity and the degradation products are transferred with the TBP into the adduct phase, which can be burned or possibly recycled. The proposed treatment for the adduct is either to split it to recover the phosphoric acid and dispose of the TBP and associated radioactivity, or to pyrolyse it, thereby recovering phosphoric acid from both the initial phosphoric acid and the TBP, and converting the degradation products to combustible hydrocarbons.

Another version of the process is to recycle or burn the diluent and recycle the TBP, or incorporate it with PVC chips to form a solid mass for disposal.

7.2.7. Biological digestion

Developed in Finland, biological digestion uses microbes to decompose organic material [47]. A volume reduction factor of between 10 to 20 can be achieved for solid organic waste. The decomposition products are biogas (not normally radioactive, except for ^{3}H- and ^{14}C-containing waste) and sludge. Most radioactive substances remain in the sludge, which can be dried and solidified for disposal, and the gas, which can be burned or released. The gas contains methane (50 to 80%) and carbon dioxide (20 to 50%), as well as minor amounts of hydrogen and hydrogen sulphide. The sludge contains inorganic materials, a dried bacteria mass and amounts of undegradable organic material.

This method was originally developed for dry waste, but it can be applied to many liquid wastes. Biological treatment of liquids has been practised for many years in non-nuclear applications, such as in conventional sewage treatment plants that rely heavily on biological activity to break down the sewage waste; more information on this method can be found in Ref. [36].

Another application of the same technology has been developed for the treatment of spent ion exchange resins. Total decomposition of the resins is estimated to be reached within one week. A flow diagram of the microbiological process for spent ion exchange resins is shown in Fig. 10.

8. TREATMENT OF SOLID WASTE

8.1. GENERAL CONSIDERATIONS

Solid waste is produced by virtually all applications and uses of radioactive materials, including both normal operations and maintenance activities. In many facilities, dealing with solid radioactive waste may be the largest part of the radioactive waste management programme. There are a number of well established technologies for handling low level radioactive solid waste. This section deals with the treatment methods for compactible and combustible waste. Non-compactible, non-combustible waste is normally subjected to direct conditioning, as described in Section 10.4.

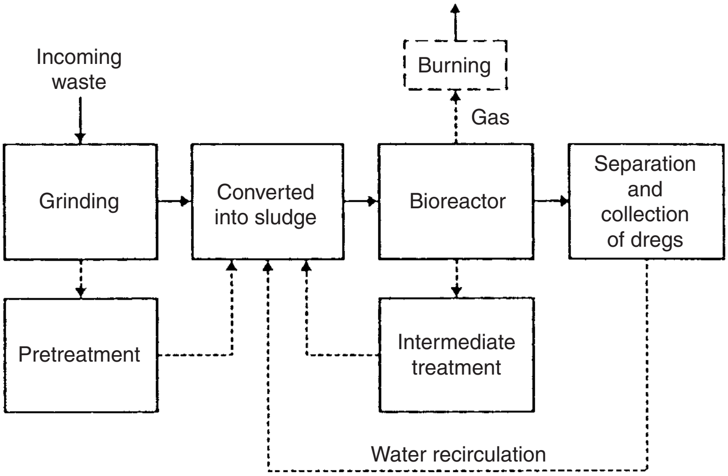


FIG. 10. Flow diagram of the microbiological process for spent ion exchange resins.

An integrated solid waste management system should consider the volumes and types of waste being handled. A detailed evaluation is required to determine whether processing is to be used, and, if so, which processes should be selected. In cases where only small volumes of waste are produced, it may not be economical to install processing equipment; in these cases direct conditioning prior to storage or disposal may be less costly. In cases where large volumes of waste are produced, the cost of processing to reduce the volume may be less than the cost of more storage and/or disposal space for the added waste. In cases where only short lived radioisotopes are involved, storage for decay and release is the preferred option, since it eliminates the costs associated with processing and conditioning the waste for long term storage and/or disposal.

An integrated strategy for solid radioactive waste management is illustrated in Fig. 11. The main components of the strategy are pretreatment, treatment, conditioning, storage and disposal.

8.2. PRETREATMENT METHODS

Pretreatment of radioactive waste is mainly performed as an appropriate preparation of the waste for facilitating subsequent treatment steps. Pretreatment actions include:

- Collection, segregation and sorting;
- Packaging for transport to an intermediate storage area or to a treatment facility;
- Size reduction (shredding);
- Decontamination;
- Decay storage.

Collection practices for solid waste from radioisotope users normally consist of distributing suitable containers throughout the working area to receive discarded radioactive materials. The containers should be marked with brightly coloured paint (normally yellow) and the radiation symbol to distinguish them from bins meant to receive inactive waste. Multiple containers, one for each category of waste produced at a facility, are often used to encourage segregation at source. For example, a four can system of incinerable, compactible, non-processible and likely clean can be used. The likely clean category is for items that are not expected to be contaminated; after monitoring they can be released to a conventional waste landfill.

Ensuring the separation of inactive rubbish from radioactive waste helps to keep the volume of radioactive waste significantly smaller than it would be if both types of refuse were disposed of together. Material handling procedures should include

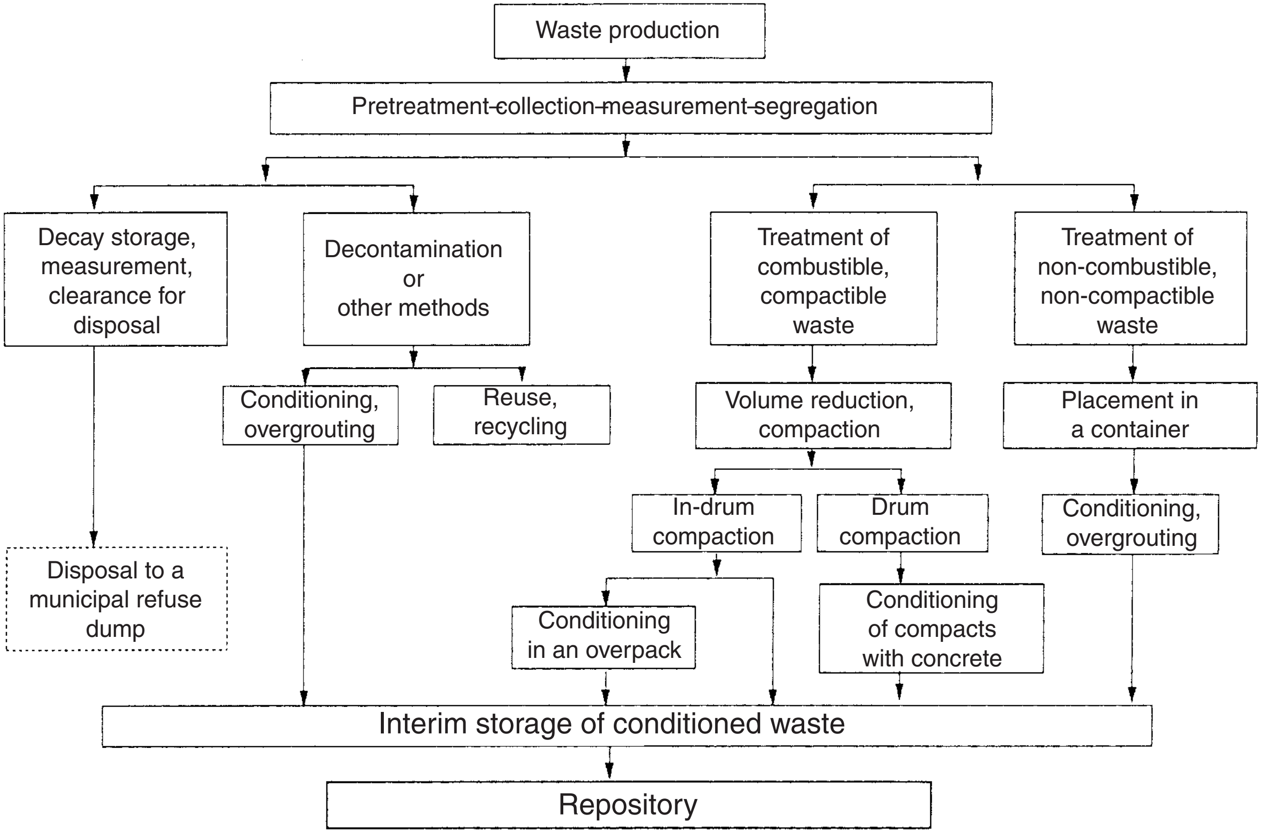


FIG. 11. The management strategy for solid radioactive waste of small nuclear research centres in developing countries.

provisions to separate products from their packaging before the product is used in a potentially contaminated area. This simple step can significantly reduce the amount of radioactive solid waste produced in a facility.

Refuse cans with foot operated lids are particularly useful in radioisotope laboratories. They should be lined inside with heavy-gauge plastic bags, which can be sealed and taken out when full. The use of plastic bags for rubbish containment has the advantage that liquids from wet materials will not seep through and contaminate the floor. Such containers may be used for the collection of combustible, compactible waste. The plastic bags should preferably be transparent to enable the contents to be visually inspected.

For non-combustible, non-compactible waste that requires a stronger container, drums may be advantageously used. For small quantities of other waste produced in gloveboxes or cells, cardboard boxes can prove useful.

Classification of the waste should be done at the sorting and segregation stages. Whenever possible, these operations should be carried out at the source of waste production, and they should be put with the packaging into appropriate containers (usually plastic bags and/or 200 L drums) bearing adequate indication (labelling and colour coding) for the subsequent management steps and treatment.

Experience shows that even at sites where waste treatment facilities are not yet available, it is highly recommended to start to segregate the waste from the beginning. Non-segregated bulk storage makes final waste treatment inevitably complicated.

Most of the waste produced in the laboratories of individual radioisotope users falls into the combustible and compactible class. Whenever solid wastes containing radionuclides with a half-life of 100 days or more (except for ^{14}C and ^{3}H) are produced, they should be stored separately for special treatment. (For ^{14}C and ^{3}H special techniques and national rules may apply [48, 49].)

Size reduction should normally be carried out in the treatment facility. However, it can be advantageous to start at the source, whenever this is possible.

Decontamination should be considered as a pretreatment step whenever the degree and/or the nature of the contamination would prohibit the treatment of the waste in an existing facility. Decontamination can be a rather complex operation necessitating special facilities, preparations and considerations, and is discussed in Section 8.3.1. However, for the pretreatment stage, the possibility of a specific, easily accomplished decontamination should be considered.

In the same context, interim storage allowing the decay of short lived radioisotopes can be an effective pretreatment method, considerably facilitating subsequent treatment steps. Decay storage is of particular importance for the type of waste dealt with in this report, since most of the radionuclides used, for example, in medicine and research are short lived and the radioactivity content is well defined. A properly administered system can result in substantial cost savings and a high degree of safety when managing this type of waste.

8.3. TREATMENT METHODS

Treatments for solid waste are used to reduce the volume of the waste and/or convert the waste into a form suitable for handling, storage and disposal.

8.3.1. Decontamination

Radioactive contamination results from the contact between radioactive materials with any surface, and occurs whenever radioactive elements are handled. Appropriate removal of the contamination from the surface could consequently convert equipment or material that had to be considered as radioactive waste into conventional waste or material that can be reused. Decontamination is thus loosely described as any process that reduces any radioactive contamination by a physical and/or chemical process. Every single piece of equipment or material that is decontaminated for reuse or for disposal as municipal refuse results in a reduction in the volume of radioactive waste. Detailed descriptions of decontamination techniques, operations and equipment can be found in Refs [50, 51]. General guidance on clearance levels for the release of decontaminated objects can be found in Refs [11–17]. Specific requirements may be found in relevant national regulations.

The process of decontamination produces both secondary liquid and solid radioactive waste. This fact must be remembered when deciding if decontamination should be applied, and, if so, which technique should be selected to restrict secondary waste arisings to a minimum and in a suitable chemical and physical form. Health and safety factors have to be considered to limit radiation doses to the operators (ALARA), as well as exposure to the hazardous chemical agents that may be used in some decontamination processes. In addition, economic evaluations should be made.

For treating solid radioactive waste generated in class A, B and C countries it is believed that decontamination should play a minor role, and will most probably only be used in exceptional cases for special items and equipment that can be reused, possibly after maintenance and/or repair operations. It should be understood that such an operation requires the appropriate technical facilities. Decontamination with a view to reaching clearance activity levels approved by the competent authorities that would allow disposal of the solid waste together with municipal refuse is, however, unlikely to play any role in treating wastes. The volume arisings of non-combustible, non-compactible solid waste that could be treated in this way are normally too small to allow the construction of the necessary sophisticated decontamination installations. The exception may be for decommissioning bulky items such as gloveboxes or animal cages.

8.3.2. Compaction

Compaction is a widely used method to reduce the volume of dry radioactive solid waste through the application of a mechanical force. There are a variety of compacting devices available that are specifically designed for radioactive waste.

In addition, commercially available presses and compacting devices designed for general rubbish often can be used for radioactive waste after appropriate modifications, such as adding secondary containments and exhaust filtering. The volume reduction factors obtained depend largely on the waste material involved and on the pressure applied, but in general are between 3 and 10. Optimum operation is achieved if the appropriate sorting and pretreatment of the waste has been accomplished.

Both low and high pressure hydraulic and pneumatic presses are in use. Forces applied can vary between 4 Mg and 1.5 Gg (4 and 1500 t); pressures usually vary between 0.2 and 80 MPa.

Owing to the varying composition of wastes, it is rather difficult to specify optimum pressure and volume reductions for particular waste treatment applications.

A case requiring particular consideration is the compaction of material showing a tendency to expand or springback after release of the compaction pressure. This includes most plastics and rubber. Compaction of waste in steel drums or compaction together with other constraints (e.g. straps or bands) can minimize or completely overcome the springback effect.

Designers and operators of compaction facilities should be aware that:

- Large, non-compactible components could damage the equipment and should be eliminated at the segregation and/or the pretreatment stage.
- Chemical reactivity of the material compacted might be enhanced (i.e. pyrophoric or explosive materials must be eliminated in the pretreatment step) and the press should be provided with appropriate fire fighting facilities.
- Absorbed or incidentally contained liquids can be released during compaction and should be collected in an appropriate drip tray system.
- Air enclosed in the primary waste packages will be released during compaction. This can lead to airborne contamination, which requires an appropriate air filtration system.
- Special precautions should be taken when compacting glass or pressurized aerosol spray cans if they are not excluded from the waste streams.

A careful selection from the commercially available equipment of that which can be best adapted to the waste category concerned in order to guarantee both conventional and radiological safety has therefore to be made.

8.3.2.1. Vacuum compaction

A recently developed vacuum compaction system is particularly suited for sealing and compacting low level radioactive and toxic waste from hospitals, medical and pharmaceutical applications, and other research activities. It can best be applied directly at the place of waste production. The system is designed to pack and seal dangerous waste as well as other materials into special plastic bags using a vacuum in connection with a welding device. The bags are manufactured from a highly chemically resistant multilayer material. All operational movements are carried out in a vacuum. During the filling operation an exhauster removes dangerous aerosols through a filter, thus preventing the ambient atmosphere from becoming contaminated. The re-entry of normal atmospheric pressure into the vacuum chamber results in a volume reduction by compacting the waste material. Generally, a volume reduction factor of at least two is achieved. The bags are then sealed by a welding device. The evacuated and sealed bags allow handling and subsequent treatment of the waste material without a direct risk of contamination. Similar systems are used in the food industry for vacuum packing various foods, and can be adapted for waste processing.

Sealing waste can also be performed without the application of a vacuum, which yields no volume reduction. This procedure is normally used for uncompactible waste and objects with sharp edges that might penetrate the bags under a vacuum stress.

8.3.2.2. In-drum compaction

In-drum (low pressure) compaction is used to reduce the volume of solid compactible waste primarily to facilitate packaging for transport, either to a waste treatment facility, where further compaction or other treatments will be carried out, or to an interim storage facility, where it will await disposal. A typical in-drum compaction unit is shown in Fig. 12.

This low pressure compaction technique, which applies forces of up to about 0.1 Gg (100 t), is mainly utilized on-site by the waste generator, but sometimes at the waste treatment facility. A typical application of a low pressure compaction technique at the waste generation site is for the simple compression of bags of rubbish into a 200 L drum. Other container geometries, such as steel boxes, can also be used, depending on the requirements of the facility. Implicit in the design of such a device is the requirement that an adequate containment and air filtration system is provided to meet the safety requirements.

In-drum compactors are reliable and trouble free. The gross volume reduction factor achievable is generally between three and five, and its capacity is about 4000 m^3 of unprocessed waste annually. The waste is generally fed manually into the compactor, hence it is limited to low dose rates and materials that are physically small enough to fit into drums. Larger objects must be cut into smaller pieces prior to compaction.

8.3.2.3. Drum compaction

The drum compaction (super compaction) process is characterized by the fact that drums containing compactible waste are compressed into stable compacts. The

FIG. 12. An in-drum compactor.

degree of compaction depends on the force of the compaction press and the physical properties of the waste material. A typical drum compaction (drum crasher) unit is shown in Fig. 13.

Drums containing either compactible waste collected at the place of production or waste already treated by in-drum compaction can be fed to the drum compaction device. In the latter case high pressure compactors using forces of 0.1 to 1.5 Gg (100 to 1500 t) are used to achieve an additional volume reduction.

As for the in-drum compaction units, very good practical experience on the performance and efficiency of drum compacting devices is available. Reliable equipment that can be adapted to the particular needs of waste treatment are available on the market; these may have both hands-on and hands-off (remote, automatic)

FIG. 13. A typical drum crusher unit.

modes of operation. However, drum compaction equipment is much more costly than simple in-drum compactors, and is not recommended for low volume producers.

8.3.3. Incineration

Incineration is an attractive process for treating combustible solid radioactive waste, and in certain cases is an advantageous means of dealing with contaminated problematic waste such as biohazardous radioactive waste, animal carcasses and other putrefied wastes.

Incineration produces a high volume reduction and converts the waste into a form suitable for subsequent immobilization and disposal. Incinerators without sophisticated off-gas cleaning or ash handling devices have relatively low investment costs, but the activity content of the waste incinerated must be restricted to levels that will not result in the exposure of operators and the general population to levels exceeding those permitted under national regulations. The use of incineration for combustible waste containing larger quantities of radioisotopes requires more advanced off-gas cleaning and maintenance systems, involving high investment and operation costs.

The principal objective of incineration is to achieve the complete combustion of the organic components of the waste into inorganic products. A radioactive waste incineration system must provide containment of the radioactive species throughout the process. The incinerator itself must provide physical containment of the volatile organic and radioactive wastes so as to avoid the escape of gases and vapours. Containment is generally provided by maintaining the combustion chamber(s) at a slight negative pressure, using an induced draught ventilation system.

In general it is not considered advisable to recommend incinerating combustible radioactive waste as a method for treating waste in Member States belonging to classes A and B. The main reasons for this are:

- The relatively low volumes of contaminated waste generated,
- The high investment and operation costs,
- The incinerator may not be employed to its full capacity.

To illustrate this it should be noted that an incinerator with a capacity of 40 kg/h would only be in operation for 30 days annually on the basis of an eight hour shift per day and a 50 to 100 m^3 generation of radioactive waste per year. Incineration of combustible radioactive waste could be, however, of interest if the incinerator is also used for the incineration of septic hospital waste or other toxic materials. To give an idea of the funding required for an incinerator based on a 40 kg/h capacity, it is estimated that the total cost of a facility would be more than US $10 million.

8.4. OPTIONS FOR TREATING BIOLOGICAL/MEDICAL WASTE

Biological and medical wastes often present additional hazards during their handling, treatment and storage. These hazards may necessitate special waste management considerations, as outlined below [2].

8.4.1. Pretreatment

8.4.1.1. Collection

Owing to the biological hazard of these radioactive wastes, it is adviseable to collect them in lidded containers; refuse cans/bins with foot operated lids are particularly recommended. They should be lined inside with heavy gauge plastic bags that can be sealed and removed. Waste collections must be scheduled such that biological materials do not deteriorate in the refuse bins.

In addition to the requirements for general radioactive waste collection, plastic bags for containing biological radioactive waste should meet certain manufacturing criteria:

- They should meet the performance specification standards of the establishment or of an appropriate medical standards setting body,
- When destined for steam sterilization they should be suitable for this treatment and carry an indicator strip to show that they have been subjected to successful treatment,
- They should be of an appropriate colour so as to be easily recognized as solid radioactive waste that may be biologically hazardous.

Special consideration should always be given to the management of contaminated sharp objects such as needles and syringes, scalpel blades, blood lancets and glass ampoules. These items are usually suitable for management as dry solid radioactive waste, although very small amounts of biological liquid might remain inside the needles.

The following requirements should be met when selecting packaging suitable for containing sharps:

- The packaging should be puncture resistant and leak proof, even if toppled over or dropped;
- It must be capable of being handled and moved within the work area while in use, with minimum danger of the contents spilling or falling out;
- The container should have an aperture which, in normal use, will inhibit the removal of the contents but will ensure that it is possible to place items into

the container using one hand without contaminating the outside of the container;
- It should have a firm closure device attached for sealing the container when it is no more than three quarters full;
- It should be marked with words similar to ‘Danger, contaminated, sharps only’.

Where treatment is by incineration, heavy duty cardboard, waxed cardboard or polyethylene/polypropylene containers, clearly labelled as sharps containers, should be used to collect the waste. Containers should be no more than three quarters filled before sealing, to prevent sharps from penetrating the container. Where there is no incineration facility available, it may be more appropriate to collect sharps in metal cans of approximately 5 or 10 L capacity. When filled, the cans should be firmly sealed and subjected to sterilization prior to compaction. The compacted tins should then be bulk collected inside a further container in preparation for their transfer to a landfill disposal site [10].

8.4.1.2. Damp waste

Damp waste should be avoided because the presence of significant moisture can lead to undesirable and possibly dangerous chemical and biological reactions while the waste is in storage or transit. Damp or wet biological material should therefore be drained, de-watered or dried to the most thorough extent possible, consistent with other safety concerns, before it is placed in waste receptacles. The addition of a moisture sorbent such as sawdust or peat moss may be advantageous. Freezing carcasses and similar remains is recommended.

In cases where damp waste is unavoidable or cannot be dried, proper packaging to contain the liquid is important. The use of plastic bags for biological radioactive waste containment has the advantage that damp waste will not seep through them. A double wrapping with plastic bags is advisable. Very heavy, wet waste should not be packaged in plastic bags as the only method of containment, owing to the possibility of the seam of the bag rupturing, with a resultant loss/seepage of the contents. When available, single use disposable plastic containers with lids (volume range 10 to 120 L) should be used. These containers, once closed and sealed, are especially useful as they are leak free, even if the container becomes accidentally inverted during further handling. Additionally, the containers have the advantage that they are suitable for incineration in furnaces designed for plastics.

8.4.1.3. Sterilization/disinfection

Where treatment by incineration is not used, one of the most important stages of biological radioactive waste management is deactivation (sterilization). Biological waste must be deactivated of all infectious agents or reliably determined non-infectious. A number of methods are used for these purposes, including:

- — Steam sterilization,
- — Chemical disinfection,
- — Dry heat sterilization,
- — Intensive gamma irradiation,
- — Microwave sterilization.

These and other methods of biological and medical waste sterilization are described in more detail in Ref. [2].

8.4.2. Treatment

8.4.2.1. Incineration

Incineration is the preferred method for treating biological radioactive waste of animal or human origin, as well as organic chemical waste. The aim of treatment by incineration is to ensure the complete combustion of the waste, producing totally sterile residues, with any emissions from the stack being kept to acceptable levels. The resulting ash and off-gas residues are thus fully deactivated chemically, all organics are destroyed and a very significant waste volume reduction is achieved. For biological radioactive waste incineration is the only fully developed technology that is capable of providing these benefits. Incineration is recommended as a part of a good waste management strategy where the volume of biological radioactive waste justifies treatment at centralized facilities.

Properly controlled, efficient incineration is an advanced and technically sophisticated treatment method. Disadvantages inherent in using this technology, however, are the high capital cost of the incinerator and off-gas system and the technical expertise required to operate and maintain the unit. For these reasons incineration may be feasible only at a central facility where other waste in addition to biological waste will be burned.

8.4.2.2. Maceration/pulverization

In cases where incineration is not available or the volumes of human and animal waste are so low that it is desirable to treat them as they are produced, it may be feasible to use maceration/pulverization techniques to render these materials liquid. The resulting liquid can than be discharged through the liquid radioactive waste route, which can include any necessary chemical deactivation to treat the biological hazard.

The apparatus used for this technique is of the same basic construction as a liquidizer used to render food products into a liquid form. It consists of a containment vessel with a lid and a series of high speed rotating blades in the base. Use of commercially available liquidizers designed for the catering industry has the added advantage that their stainless steel construction can withstand the addition of chemicals such as sodium hypochlorite along with the water to achieve both liquidization and chemical disinfection of the waste.

8.4.2.3. Chemical methods

Mummification. Putrifiable solid biological waste can be collected in plastic bags. If refrigerated storage space is not available, it is useful to add sawdust or diatomaceous earth to absorb any emanating fluids. The addition of formaldehyde, chlorinated lime or hypochlorite solution may also be advantageous. A small amount of dilute formaldehyde delays decomposition; concentrated formaldehyde (40%) results in mummification of a small animal carcass after a period of about one year. Handling formaldehyde is hazardous, and proper precautions, including good ventilation, are necessary. After mummification, waste can be placed in a waste drum and the drum filled with cement grout. This method, however, is not a preferred or recommended means of treatment and is discussed only as an option for Member States without an incineration capability.

Dissolution. This is not a strongly recommended treatment method for solid biological radioactive waste, but in circumstances where no suitable alternative treatment is identified it may have a role. This technique involves the use of concentrated acids or bases (HCl, HNO_3, NaOH) to destroy the structure of solid radioactive materials and render them liquid.

The severity of this treatment may also satisfactorily eliminate any biological hazard associated with the waste. The waste may then be discharged after being neutralized and diluted, if necessary, in compliance with the regulations governing both chemical and radioactive liquid discharges. If the resulting liquid cannot be discharged, then further treatment may be appropriate.

9. IMMOBILIZATION MATERIALS AND PROCESSES

Waste immobilization has become an important step in the field of waste management and the philosophy of environmental containment. This step converts waste, usually a liquid or semi-liquid, into a solid form that can be handled, stored and disposed of more safely and conveniently. It can reduce the volume of the waste by removing liquids and reduces the potential for radionuclides to move through the geosphere after disposal.

There are a variety of matrix materials and techniques available for immobilizing and conditioning waste. For long term storage and disposal the method of solidification used should not be a reversible process that allows the solid to return to a liquid form. Estimation of the rate of leaching from a solidified matrix during disposal is one of the important considerations in the assessment of a solidification method, as it will strongly influence the amount of treatment, containment and surveillance that will be needed. Low matrix solubility improves the safety of waste management through isolation, which further reduces the likelihood of radionuclide release. For short term storage, or to convert temporarily a liquid into a solid for material handling purposes, a reversible process may be used (e.g. absorption of oil on peat moss prior to incineration).

In any immobilization process where radioactive materials are used, the process and operational conditions can become complicated if remotely operated and maintained equipment is required. Attention must be given to reliable, simple, rugged equipment, which may have advantages over complex or sensitive equipment.

In this section emphasis has been placed on those options available commercially and that have, to various degrees, been demonstrated to be viable. At the same time, it is recognized that other matrices are being researched as possible for future options. Included in these options are modified sulphur cement, polyethylene and other thermoplastic materials. However, although some of these other methods have reached advanced stages of development, their viability has yet to be demonstrated on a commercial scale and it is not possible to assess fully their suitability at this stage. It should also be pointed out that problems have been encountered with the solidification of some waste streams, and waste generators frequently use high integrity containers (HICs) to provide the required stability. These containers are generally very expensive, but this disadvantage may be offset by the simplified processing of the waste. Waste generators prefer HICs for many reasons, including ease of use and lack of on-site solidification capability. In cases where only small volumes of waste are handled, the extra cost of HICs can be offset by not having to purchase additional processing equipment.

9.1. MATRIX MATERIALS

There is a wide range of potential matrix materials available for conditioning liquid and wet solid wastes [52–54]. The selection of any particular material will be governed not only by the waste form criteria stipulated by the licensing and regulatory bodies, but by the composition of the waste and the extent and type of treatment prior to the conditioning step.

A wide divergence of regulatory, process and product requirements has led to the investigation and adoption of a variety of conditioning matrices for waste immobilization. The matrix materials that are available commercially and have been demonstrated to be viable to various degrees are:

- Hydraulic cements (with and without additives),
- Bitumen,
- Polymers.

In this section emphasis is placed on ordinary Portland cement, which is the most common type of cement used for immobilizing liquid and wet solid wastes worldwide. A brief description is also given of several of the more common Portland cement based mixtures currently used to overcome the incompatibility problems associated with the chemical composition of certain types of waste.

9.1.1. Hydraulic cements

The term hydraulic cement is used in this report to describe inorganic materials that have the ability to react with water at ambient conditions to form a hardened mass. The term concrete, however, is used to describe a mixture of hydrated (hardened) cement containing solid waste aggregates such as ion exchange resins, salts and sludges.

The most common cements are those based on calcium silicates, such as the Portland cements.

9.1.1.1. Portland cement

Portland cement is produced by heating clay materials with lime at a high temperature (>1500°C). These materials form a solid mass (clinker) that, when cooled, is mixed with gypsum (calcium sulphate) and pulverized.

Portland cement is composed chiefly of silica (SiO_2), lime (CaO) and alumina (Al_2O_3), but also contains small quantities of magnesia (MgO), ferric oxide (Fe_2O_3), sulphur trioxide (SO_3) and other oxides introduced as impurities in the raw materials used in its manufacture. When these components are mixed together they form the four basic compounds of Portland cement: tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite. Table XIX shows the oxide compositions and the abbreviations for these compounds used by cement chemists. Each of the compounds shown in Table XIX contributes towards the behaviour of the cement in interms of its strength, time of setting, heat generation and resistance to shrinkage during the curing stages [53].

TABLE XIX. PRINCIPAL COMPOUNDS IN PORTLAND CEMENT

Compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S
Dicalcium silicate	$2CaO \cdot SiO_2$	C_2S
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

TABLE XX. TYPICAL COMPOSITIONS OF COMMERCIALLY USED PORTLAND CEMENT (WEIGHT %)

Constituent	Chemical formula	Cement type				
		I	II	III	IV	V
Tricalcium silicate	$3CaO \cdot SiO_2$ (C_3S)	50	42	60	26	40
Dicalcium silicate	$2CaO \cdot SiO_2$ (C_2S)	24	33	13	50	40
Tricalcium aluminate	$3CaO \cdot Al_2O_3$ (C_3A)	11	5	9	5	4
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ (C_4AF)	8	13	8	12	7
Others		7	7	10	7	7

Since an infinite number of cements can be made by varying its composition, five types of Portland cement have been recognized internationally. Typical compositions of commercially available Portland cements are given in Table XX [54].

Type I, normal Portland cement or ordinary Portland cement (OPC) as it is called in some parts of the world, is the most commonly used when the special properties of the other types are not required, for example when it is not subject to sulphate attack from waste, or where the heat generated by the hydration of the cement will not cause an unacceptable rise in temperature.

Type II, modified Portland cement, has a lower rate of hydration than type I and generates heat at a slower rate. It also has improved resistance to sulphate attack and is intended for use where added precautions against moderate sulphate attack are important.

Type III, high early strength cement, develops strength rapidly as a result of its high tricalcium aluminate and tricalcium silicate content. This rapid strength development is, however, accompanied by a high rate of heat production, which may preclude the use of type III cement for massive waste/cement monoliths.

Type IV cement is a low heat cement that can be used primarily for massive waste/cement monoliths. The low rate of heat production in this cement type is attributable to its high dicalcium silicate content and corresponding low tricalcium silicate and tricalcium aluminate contents.

Type V cement is sulphate resistant owing to its low tricalcium aluminate content. It is a special cement intended for use in monoliths exposed to severe sulphate action. It has a slower rate of strength gain than normal Portland cement.

Portland cement types I, II and III are normally those used for radioactive waste solidification. While type II has an enhanced resistance to sulphate attack, sodium sulphate solutions have been successfully solidified, with all three types having roughly the same loadings. Boric acid can be solidified if an alkaline material (e.g. slaked lime or NaOH) or sodium silicate is added to the cement or the alkalinity of the waste is increased to pH 8 to 12. Types I, II and III have been shown to work with these additives. Type III, however, is preferred for boric acid type liquid waste because of the rapid curing characteristics of this cement, which in many cases counteracts the retarding effects induced by boric acid.

When Portland cement is mixed with water, its constituent compounds undergo a series of chemical reactions that are responsible for the eventual hardening of the cement. The reaction between the compounds of the cement and water is called hydration. Hydration reactions can be written for each of the major compounds present in Portland cement; however, the resultant equations are not stoichiometrically rigorous because of variations both in the products formed and their compositions. Basically, the two calcium silicates that constitute about 75% of a Portland cement by weight react with water to produce two new compounds: calcium hydroxide and a calcium silicate hydrate called tobermorite gel [4]. The tricalcium aluminate and tetracalcium aluminoferrite combine with considerably more water on a molar basis than do the calcium silicate compounds.

Each of the compounds formed play an important role in the properties of the cement. By far the most important is tobermorite gel, which is the main cementing component of concrete. Properties such as setting and hardening, strength and dimensional stability depend primarily on tobermorite gel.

The water/cement (w/c) ratio is probably the most significant single item affecting the strength and chemical resistance of a concrete mix. In making concrete, more water is used than required for hydration. The extra water is necessary to make a workable and more mobile mixture. The amount of water used, however, can be minimized by trial and error techniques and by the use of water reducing admixtures for different mixtures and applications. Improperly compacted concrete can also produce high void percentages, but basically the void volume in cement depends mainly on the amount of water mixed with the cement at the beginning of the process.

Permeability is also more pronounced the higher the w/c ratio. The relationship between permeability and the w/c ratio of mature Portland cement pastes is shown in Fig. 14. Increasing permeability results in increased leachability and deterioration of the concrete when exposed to aggressive groundwaters. The detrimental effects of the

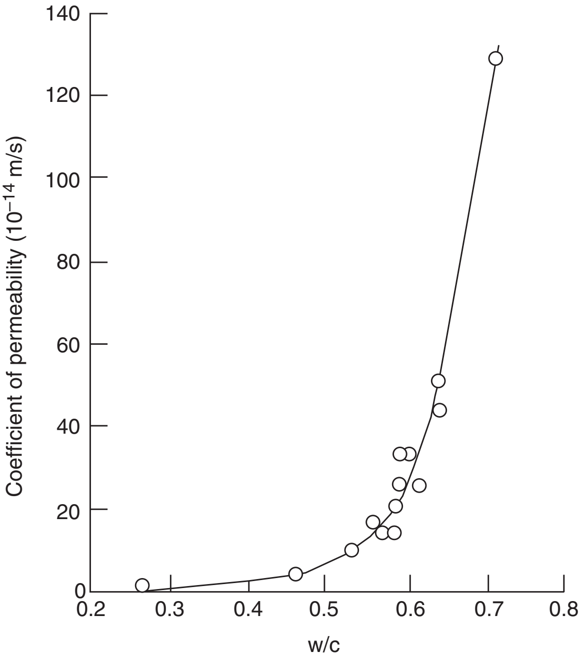


FIG. 14. Relationship between permeability and water/cement (w/c) ratio.

freeze–thaw cycle on concrete can be minimized to ensure better durability by use of an appropriate w/c ratio. The large void volume resulting from high w/c ratios affects practically all of the mechanical durability and chemical properties of concrete.

The practice of immobilizing radioactive waste with ordinary Portland cement began during the early years of the nuclear industry. This was primarily due to its low cost, availability and compatibility with aqueous waste. It was soon realized, however, that specific wastes, such as those shown in Table XXI, interact with the cement components to inhibit or retard the hydration reaction [6]. To overcome these effects, one or more selected additives were added to Portland cement mixtures. Several of the more successful mixtures have been commercialized and are identified in Table XXII.

9.1.1.2. Masonry cement

Masonry cement is a mixture of Portland cement and slaked lime ($Ca(OH)_2$). As used for radioactive waste solidification, Portland cement and slaked lime are typically combined in equal proportions. In the presence of water, the extremely high

TABLE XXI. CHEMICAL COMPATIBILITY OF WASTES WITH HYDRAULIC CEMENTS

Waste type	Compatibility
Organic ion exchange resins	Poor/good[a]
Precipitation sludges	Good[b]
Boric acid wastes	Poor/good[a, b]
Sulphate wastes	Fair
Nitrate wastes	Good
Phosphate wastes	Good
Detergent solutions	Poor/good[c]
Complexing agent wastes	Poor
Oils, organic liquids	Poor/good[d]
Acidic wastes	Poor/good[e]

[a] Good with special cements and calcium hydroxide.

[b] Good with admixtures of, for example, sodium silicate.

[c] Good with anti-foaming agents.

[d] Good with emulsifying agents.

[e] Good after neutralization.

TABLE XXII. MODIFIED PORTLAND CEMENTS

Type	Additive	Use	Function
Masonry cement	Lime	Boric acid	Adjusts pH
Portland sodium silicate cement	Sodium silicate	Organic liquids	Accelerates set, reduces porosity
Portland pozzolanic cement	Reactive silica	Sulphate	Reacts with $Ca(OH)_2$, reduces porosity
Portland blast furnace slag cement	Slag	Sulphate	Reacts with $Ca(OH)_2$

alkalinity induced by the slaked lime produces a rapid setting cement. Masonry cement is particularly useful for solidifying wastes such as boric acid and borate salts, bead resins and filter sludges, which tend to inhibit or retard cement hydration. Masonry cement also provides advantages over Portland cement in the increased rate of cement hydration reactions caused by the alkalinity of the slaked lime. The bulk density of masonry cement is about 35% less than that of Portland cement. Masonry cement can, at least in some cases, incorporate more waste than Portland cement. While substantial, the compressive strength of masonry cement paste is significantly less than that obtained with Portland cement under similar conditions [55, 56].

9.1.1.3. Portland sodium silicate cement

Cement–sodium silicate binder uses either sodium silicate (waterglass) or sodium metasilicate as an additive to Portland cement. Sodium silicate is a liquid additive, while sodium metasilicate is a soluble granular solid. The action of both additives during solidification is similar. Multivalent cations in the waste (as well as soluble multivalent cations in the cement) react with the sodium silicate additive to form low solubility silicate compounds that precipitate as a gel. Because this precipitation reaction is rapid, the sodium silicate additive is normally added after the cement and the waste have been mixed. Mixing after sodium silicate addition is limited so as to minimize disruption of the precipitate gel network that forms. This produces a waste–cement mixture that achieves an apparent set in a short time (in minutes) owing to the precipitate gel. The sodium silicate also accelerates the actual setting of the cement owing to its high alkalinity, although the formation of stable cement mineral hydrates (hardening) requires additional time, similar to that required for hardening in unmodified Portland cements.

Cement–sodium silicate binder is reported to provide advantages over Portland cements for the solidification of boric acid, borate salts and organic liquid wastes because it sets so rapidly. The use of sodium silicate as an additive is also reported to result in a higher waste packaging efficiency and an increased liquid tolerance.

9.1.1.4. Portland pozzolanic cement

A pozzolana is a material that is capable of reacting with lime in the presence of water at ordinary temperatures to produce cementitious compounds. Italian pozzolana, trass and Santorin earth are examples of naturally occurring pozzolanas of volcanic origin. Artificial pozzolanas are prepared by burning at suitable temperatures certain clays, shales and diatomaceous earths that contain clay. Diatomaceous silica and some natural amorphous silica deposits may also form pozzolanas, either with or without a heat treatment. Pulverized fuel ash (fly ash) is also used as a pozzolana. Pozzolanic cements are produced by grinding together Portland cement clinker and a pozzolana, or by mixing together a hydrated lime and a pozzolana [4]. Pozzolaic cements are particularly suitable for immobilization since the permeability of the concrete is greatly reduced by the continuous filling of the pore volume during the hydration reaction. The absence of leachable free lime in the concrete also contributes to its low permeability and high resistance to sulphate attack from sulphate bearing waste streams or aggressive groundwaters.

9.1.1.5. Portland blast furnace slag cement

Blast furnace slag is a by-product obtained in the manufacture of pig iron and is formed by the combination of the earthy constituents of the iron with limestone flux [53].

Portland blast furnace cement is a mixture of Portland cement and granulated slag containing anywhere from 20 to 95 wt% slag, depending on standards established in different countries. Since some slags hydrate very slowly on contact with water, its hydration is activated by the addition of other compounds, such as calcium hydroxide, calcium sulphate, sodium carbonate and sodium sulphate. Lime for activation is most conveniently supplied by the hydration of the Portland cement in the mixture. The rate of the hydration reaction is mainly a function of slag concentration in the cement mixture. The higher the Portland cement concentration, the faster the hydration reaction [53].

In addition to a reduced heat of hydration, the setting rate of blast furnace slag cements is also reduced. This may be beneficial in processing systems where quick setting cement is not desirable. Blast furnace slag cements have a lower permeability than Portland cements, which contributes to the lower diffusion rate of ions through the hardened cement and improved stability in the presence of salts such as chloride and sulphate [57].

9.1.2. Bitumen

Bitumen is a thermoplastic material and can behave mechanically as either a viscous liquid or a solid, depending on its temperature. The use of bitumen to solidify low level radioactive wastes has been successfully applied on an industrial scale for many years in different countries [58]. Bitumen (asphalt) is a mixture of high molecular weight hydrocarbons that is obtained as a residue in petroleum or coal tar refining. It has two major components: asphaltene compounds, which give bitumen colloidal properties, and malthene compounds, which impart viscous properties.

Several types of bitumen products are available, including direct distillation products, oxidized (or blown) bitumen, cracked bitumen, pitches and emulsified bitumen [59]. The properties of these various classes of asphalt vary widely. The two types of bitumen most widely used for immobilizing radioactive waste are straight run distillation bitumen and oxidized (air blown) bitumen. Emulsified bitumen has also been used, but to a lesser extent.

9.1.3. Polymers

Polymer processes have only been used to a limited extent for immobilizing radioactive waste. Generally, they have been applied to ion exchange resins owing to the difficulties encountered when using cement or bitumen [60].

9.2. IMMOBILIZATION PROCESSES

Several different processes are available for processing radioactive waste using the matrix materials discussed in Section 9.1. In general, the following parameters may be used to categorize radioactive waste immobilization processes:

- The matrix material,
- The type of mixing process,
- The size and type of container.

Some systems are built to use a single type of container, while other systems can use many different types, and some systems are designed to use different types of matrix materials. Processes involving cementation and bituminization have been extensively used throughout the world for many years. Polymer processes have been used infrequently in the past but are slowly gaining momentum as waste form performance requirements become more stringent. Normally, waste immobilization is performed in fixed installations at the waste generation site or at a centralized facility, but mobile systems have been developed that can be moved from one site or facility to another as the need arises.

9.2.1 Cementation processes

9.2.1.1. In-drum mixing

In-drum mixing processes involve mixing the waste and cement inside a container that can also be the final product container. The components are blended until a homogeneous mixture is obtained. After mixing, the cement–waste mixture is allowed to set, the container is capped with fresh cement to minimize void spaces and to avoid surface contamination, and a lid is fitted. A simplified process flow diagram for a cement in-drum container system is shown in Fig. 15 [6].

The mixing techniques used for in-drum processes include:

- Mixing with a reusable mixing element that stirs the contents of the container and is removed before the container is capped and the mixture sets. A disadvantage of this process is that the residue on the mixing paddle must be removed and the paddle washed to prevent area and container contamination.
- Mixing with a disposable mixer that stirs the contents of the container and is then left in the container. This is referred to as the lost paddle approach and involves the use of a paddle that is inexpensive to fabricate but capable of producing a homogeneous mix.

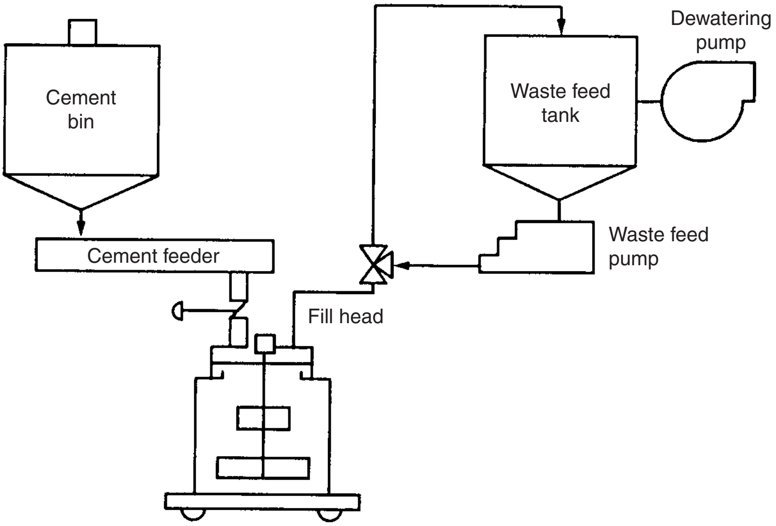


FIG. 15. Simplified process flow diagram for an in-drum cement immobilization system.

9.2.1.2. Roller mixing

Roller mixing is a relatively simple in-drum mixing system that was used for the cementation of liquid waste in some early immobilization plants. This system is probably the easiest to operate and requires the minimum amount of space and equipment. In operation, cement and liquid wastes are pumped into a disposal drum (usually 220 L), allowing a sufficient amount of void space within the container for efficient mixing to take place during the rolling stage. After sealing, the drum is placed on rollers in a horizontal position, where mechanically driven rollers rotate the drum to induce a mixing action. Although this system is no longer used, it may have applications for solidifying low level waste where only a small throughput of drums is required [61].

9.2.1.3. Tumble mixing

Figure 16 illustrates an in-drum mixing technique in which the drum and its contents are attached to a tumbling frame and rotated end over end in order to mix the contents thoroughly. In this process dry cement and a disposable mixing weight are placed in a 220 L drum, followed by the waste and any additional chemicals. The drum is then capped prior to end over end tumbling. For this system, cap removal, filling, cap replacement and mixing is an automatic operation. Although tumbling

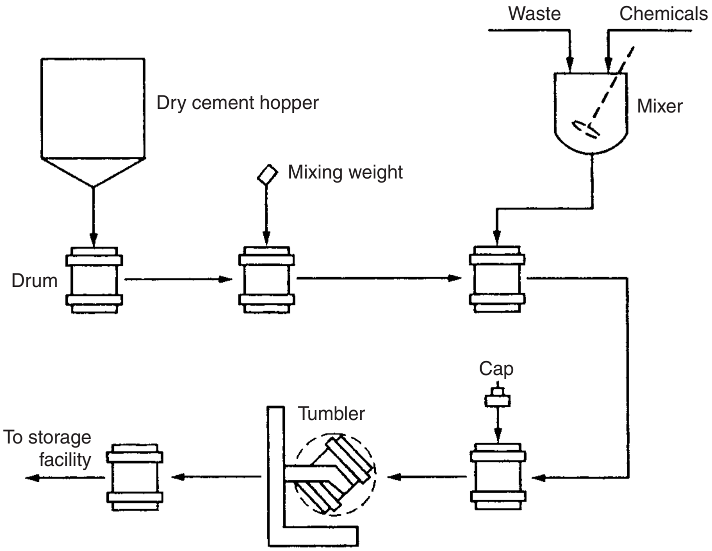


FIG. 16. The tumble mixing process.

provides better mixing than the roller process, homogeneous mixing cannot always be assured [52].

9.2.1.4. In-line mixing

In-line mixing processes combine waste, any additives, water and cement before they are placed into a disposal container [52]. A typical in-line cementation process is shown in Fig. 17. In this process the cement and the waste are separately metered into the mixer. The cement is fed by a screw feeder, while the waste is fed by a positive displacement pump. The cement/waste mix is released directly from the mixer into the container. The level of cement/waste in the container is monitored, possibly by ultrasonic or contact probes. The container is then sealed, decontaminated, monitored and sent for storage. The waste tank and mixer can be flushed through after each run. If desired, the rinsing water can be stored and used to prepare the feed slurry for the next run.

9.2.1.5. Status of waste conditioning by cementation

Conditioning of liquid radioactive waste concentrates by cementation has developed as a standard solidification technique in waste management. It is practised

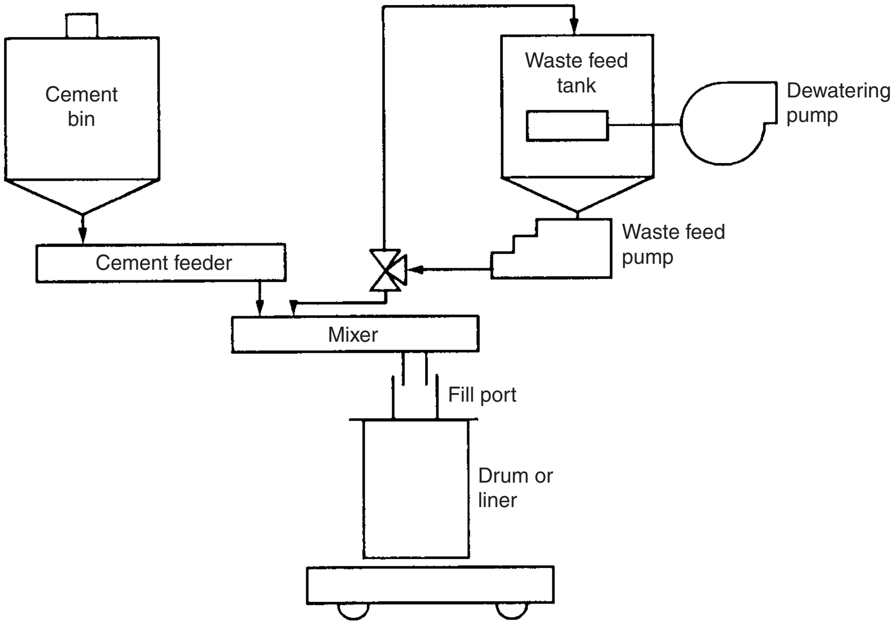


FIG. 17. The in-line mixing cementation process.

on different scales, depending on the specific local situation with respect to the types and volumes of waste. Versatile cementation units can be designed that take account of possible fluctuations in waste compositions. In addition, waste conditioning that applies elaborate mixtures of cement and additives is common practice and assures final waste products of a high quality and standard. There are presently a large number of cementation units in operation at various nuclear facilities throughout the world.

9.2.2. Bituminization processes

Bitumization is a proven immobilization process for a wide variety of radioactive wastes. Both batch and continuous processes have been used, but the continuous process is generally preferred because of the higher throughput. The primary equipment of a continuous process is either a multiple screw extruder or a wiped thin film evaporator, both of which are expensive. The process is also energy intensive owing to the need to heat equipment, bitumen storage tanks and feed lines. Examples of worldwide installations for the bituminization of waste can be found in Ref. [59].

9.2.3. Polymer processes

Polymer processes have only been used to a limited extent for immobilizing radioactive waste, mainly for ion exchange resins. Both thermoplastic and thermosetting polymers have been used. In most cases the waste must be predried when polymers are used as the immobilization matrix; an exception to this is if a water extendible vinyl ester or polyester resin forms the matrix. Generally, polymer processes are of the batch type. A description of particular polymer processing facilities can be found in Ref. [60].

9.3. PROCESS SELECTION

9.3.1. General

This section attempts to provide guidance to Member States in classes A, B and C in the selection of the appropriate processes for treating radioactive concentrates. It is assumed that the differences in volume, type and radioisotope content of waste for these Member States will present different requirements, which may influence an individual State's preference for a given process.

Typical volumes and characteristics of the radioactive concentrates and the importance of this characterization have been discussed in Section 2 of this report. These values should be considered in both process selection and sizing of the necessary equipment. The physical and chemical properties of the immobilized waste are also an important consideration in process selection. A major factor in process selection is that of the resources required; these include the availability of matrix materials, financing, infrastructure and the skills of the workforce. For example, with regard to personnel it is necessary that supervisors have enough appropriate training in and experience of radioactive waste management practices to ensure that process operations meet the appropriate safety, regulatory and quality assurance standards. Plant operators require adequate knowledge of the process equipment in order to operate it correctly; it may be appropriate to select processes that have parallels in indigenous non-nuclear industries.

9.3.2. Guidelines for process selection

9.3.2.1. Process evaluation

Tables XXIII and XXIV provide an evaluation of cementation and bituminization processes, respectively [61]. The need with the bituminization processes for high temperature operation, and the associated potential fire hazard,

TABLE XXIII. EVALUATION OF CEMENTATION PROCESSES

Process	Advantages	Disadvantages
In-drum mixing	1. Good product homogeneity 2. Simple processing equipment 3. Good quality control 4. Suitable for mixed waste streams 5. Lost paddle variant avoids secondary waste generation and reduces the potential to spread contamination 6. Suitable for small waste volumes	1. Fixed paddle variant generates secondary waste from paddle cleaning and the potential for spreading contamination 2. Waste pretreatment may be necessary
Roller mixing	1. Simple processing equipment 2. Suitable for mixed waste streams 3. Avoids secondary waste generation 4. Suitable for small waste volumes	1. Uncertain product homogeneity 2. Poor quality control 3. Waste pretreatment may be necessary
Tumble mixing	1. Suitable for mixed waste streams 2. Avoids secondary waste generation 3. Suitable for small waste volumes	1. Uncertain product homogeneity 2. Poor quality control 3. Waste pretreatment may be necessary 4. Complex, expensive processing equipment 5. Significant maintenance requirements
In-line mixing	1. Good product homogeneity 2. Good quality control 3. Suitable for large volumes of mixed waste streams 4. Continuous operation	1. Secondary waste generation 2. Waste pretreatment may be necessary 3. Complex processing equipment 4. Significant maintenance requirements

suggests that cementation is the preferred process option in class A, B and C countries.

Because of the very limited use of polymers as immobilization matrices for waste concentrates, and the necessity in most cases for predrying the feed, these matrices and their processes cannot be recommended for use in most applications described in this report.

TABLE XXIV. EVALUATION OF BITUMINIZATION PROCESSES

Process	Advantages	Disadvantages
Batch	1. Suitable for small waste volumes 2. Good product homogeneity 3. Suitable for mixed waste streams 4. Good quality control 5. High waste loading	1. High temperature process 2. Secondary waste treatment of condensates 3. Waste pretreatment may be necessary 4. Possible fire hazard
Continuous extrusion	As 2 to 5 above	As above, plus: 5. Expensive equipment
Continuous film evaporator	As 3 to 5 above	As above, plus: 6. Significant maintenance requirements

TABLE XXV. QUALITATIVE COMPARISON OF THE PROPERTIES OF IMMOBILIZED WASTE FORMS

Leach resistance	Cement < polymers < bitumen
Radiation resistance	Polymers < bitumen < cement
Mechanical stability	Bitumen < polymers < cement
Fire resistance	Bitumen ≤ polymers < cement
Waste loading	Cement < polymers ≤ bitumen
Cost	Polymers > bitumen > cement

9.3.2.2. Waste form properties

The physical and chemical properties of immobilized waste forms have to be adequate to meet any storage, transport and disposal facility conditions and regulatory requirements. For example, the requirements for leaching resistance, waste form comprehensive strength, fire and impact resistance during transportation, chemical stability and radiation stability may differ between Member States, and also depend on the final disposal acceptance criteria. The waste form producer needs to show that its waste forms meet the relevant requirements.

Table XXV gives a qualitative ranking of the waste forms produced by cementation, bituminization and polymer immobilization. The relative cost of waste forms using these three matrices is also shown. It is clear from the table that cemented waste forms are superior in all respects, with the exception of waste loading and leachability.

10. CONDITIONING OF SPECIFIC WASTE TYPES

10.1. CONDITIONING OF ION EXCHANGE RESINS, SLUDGES AND CONCENTRATES

The small estimated waste arisings of ion exchange resins, evaporator concentrates and precipitation sludges suggest that the preferred strategy is to conduct a few conditioning campaigns per year. Typically, a small scale in-drum cementation facility produces about four drums per day. All of the waste streams may be combined (blended) for conditioning, as shown in Fig. 18 [61]. The operations described below should be undertaken.

Buffer storage. Waste should be accumulated in tanks until there is sufficient volume for a suggested twice yearly conditioning campaign. The recommended capacities of these tanks are 10 m^3 for precipitation sludges and 1 m^3 each for ion exchange resins and evaporator concentrates. These tanks should have provision for mixing, sampling and discharging.

Analysis. Before starting a campaign each waste should be analysed for chemical composition, radionuclide inventory and density. This provides the basis on which the operating conditions of the cementation will be defined, and for confirmation of the waste characterization data provided by the waste producers.

Blending and pH adjustment. The waste should be blended in the proportions established by the proof tests and adjusted to pH7.

Cement metering. The contents of six 50 kg bags of cement should be metered into a 200 L drum.

Blended waste metering. The blended waste should be metered in batches (in total 100 L) during slow mixing. Mixing should be continued until a homogeneous mixture is produced; this may take up to 15 min. After complete mixing the stirrers should be removed from the drum by lifting the planetary gear unit. After dripping off the cement paste from the stirrers and subsequent cleaning, the drum should be moved to the cement curing position and allowed to stand for 24 h in order to solidify. Campaign operation of the in-drum mixer requires only decontamination of the stirrers at the end of the campaign. This can be achieved by wiping with a suitable material (e.g. tissues) or by operating the stirrers in a drum filled with water. The resulting contaminated effluent can be used several times.

Quality check. The specified quality control checks on the waste form need to be carried out. These may include checks for the absence of free liquids and confirmation of crack free solid formation. If the waste form is satisfactory, the drum should be capped with a layer of pure cement and allowed to stand while the capping cement solidifies. The drum lid should then be fitted and secured. A contamination check and

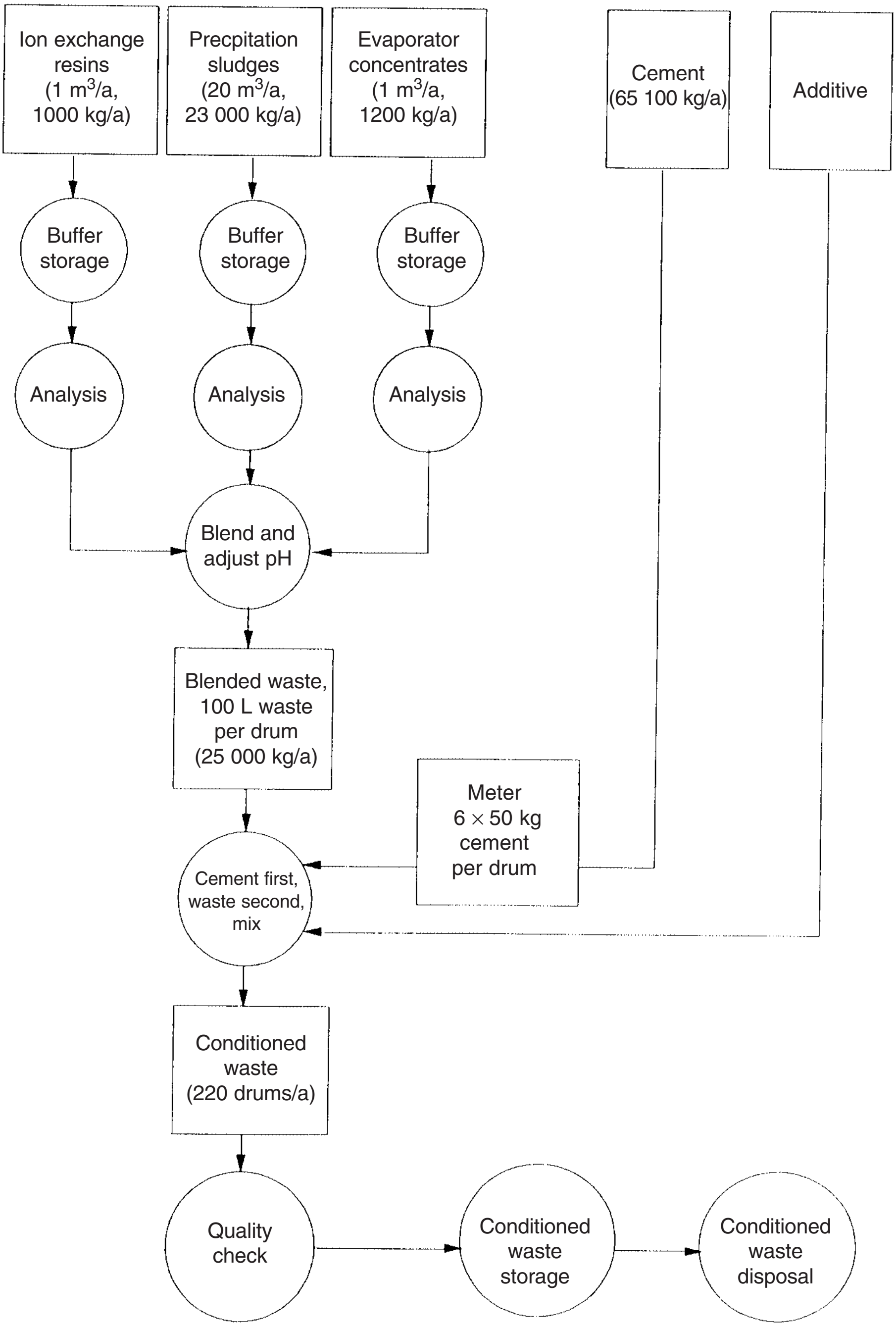


FIG. 18. *Flow diagram of the combined in-drum cementation process.*

decontamination of the drum surface, if needed, should be carried out and the surface dose rate measured.

Storage of conditioned waste. The waste drum should be transferred to the storage building.

Disposal of conditioned waste. When a disposal facility (repository) becomes available, the waste drum may be transferred from storage to the disposal facility.

Separate conditioning of ion exchange resins is advisable when the precipitation sludges and/or evaporator concentrates contain high soluble salt loadings, owing to the possibility of these salts replacing radionuclides fixed on the resins. In this situation slightly different procedures are recommended, as shown in Fig. 19.

For the waste conditioning processes shown in Figs 18 and 19 the waste compositions shown in Table XXVI have been assumed.

The waste loading in cement in Fig. 18 has been set at a low value. In practice a higher waste loading could be tolerated, thereby reducing the number of conditioned waste drums by a factor of four. However, in order to achieve this it would be necessary to introduce a further waste concentration step, such as filtration. This would lead to a more complicated and expensive process.

Figures 18 and 19 assume that a simple, straightforward cementing recipe can be used. Samples of the waste should be taken and small scale cemented waste forms prepared to confirm that the recipe is suitable. If it is not suitable, chemical pretreatment and adjustment of the recipe may be necessary, taking account of the results obtained in the analytical characterization of the waste streams. The suitability of adjusted recipes to provide an acceptable waste form should be confirmed by proof tests before undertaking full scale operations [52, 62].

10.2. CONDITIONING OF ORGANIC LIQUIDS

10.2.1. Treatment with absorbents

The treatment of organic liquid radioactive waste with absorbents is a simple way of converting a liquid into a solid form. As long as there is an excess of absorbent

TABLE XXVI. ASSUMED WASTE FEED COMPOSITIONS

Waste type	Density (kg/m^3)	Dry solids weight (%)	Water weight (%)
Precipitation sludges	1150	12	88
Evaporator concentrates	1200	20	80
Ion exchange resins	1000	50	50

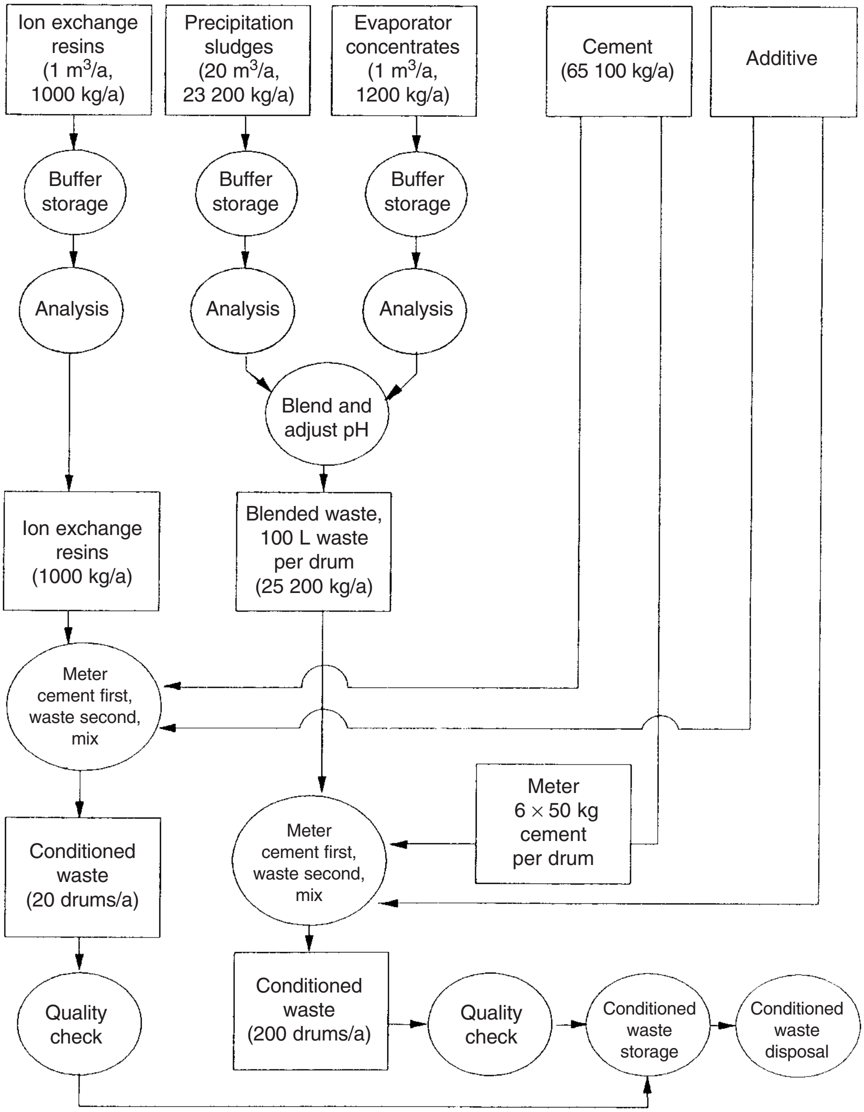


FIG. 19. Flow diagram of the separate in-drum cementation process.

there is no need for mixing; liquid waste can be added to the absorbent in a suitable container and in due course all the liquid will be taken up. This technique has been routinely used for the solidification of radioactive turbine and pump oil [63]. The following categories of absorbent are commonly used:

— Natural fibres (for example sawdust, cotton),
— Synthetic fibres (for example polypropylene),
— Vermiculite (for example mica),
— Clays,
— Diatomaceous earth,
— Imbiber beads (for example alkyl styrene polymer).

The use of absorbents converts liquid waste into a form that can vary from loose, dry particles to a jelly-like solid. The waste forms have no special integrity and are only restrained from dispersing by their containers. As shown in Table XXVII, the absorption efficiency of the different absorbents may vary by a factor of two to three, and the waste volume increase can be up to almost 300%.

The suitability of absorption alone for the solidification of organic liquid waste is moderate; the process efficiency can be adversely affected by the presence of water or other ionic contaminants, and variations in waste viscosity can cause significant reductions in the quantity of liquid absorbed. Finally, the waste form is readily dispersible in air or water if the product container is breached. This process is probably the simplest technique for converting organic liquids into a solid form and is practised extensively in many areas.

10.2.2. Cementation

Cement by itself has limited efficiency in solidifying organic liquid waste. Only about 12 vol. % of oil can be incorporated directly into cement and still retain a waste form that is dry and monolithic. However, significant increases in waste loadings can be obtained when emulsified and multiphased (oil/water/solvent) wastes are used. Mixing the components requires only an in-drum mixer or drum roller. The liquid waste solidification with cement process is shown in Fig. 20.

TABLE XXVII. PERFORMANCE OF ABSORBENTS FOR ORGANIC LIQUIDS

Product	Absorbency waste/sorbent (ratio by volume)	Organic waste by volume (%)	Volume increase (%)
Natural fibres	0.90	47	111
Synthetic fibres	0.80	44	125
Clays	0.60	33	167
Diatomaceous earth	0.65	40	154
Vermiculite	0.35	26	286
Imbiber beads	4.00	80	25

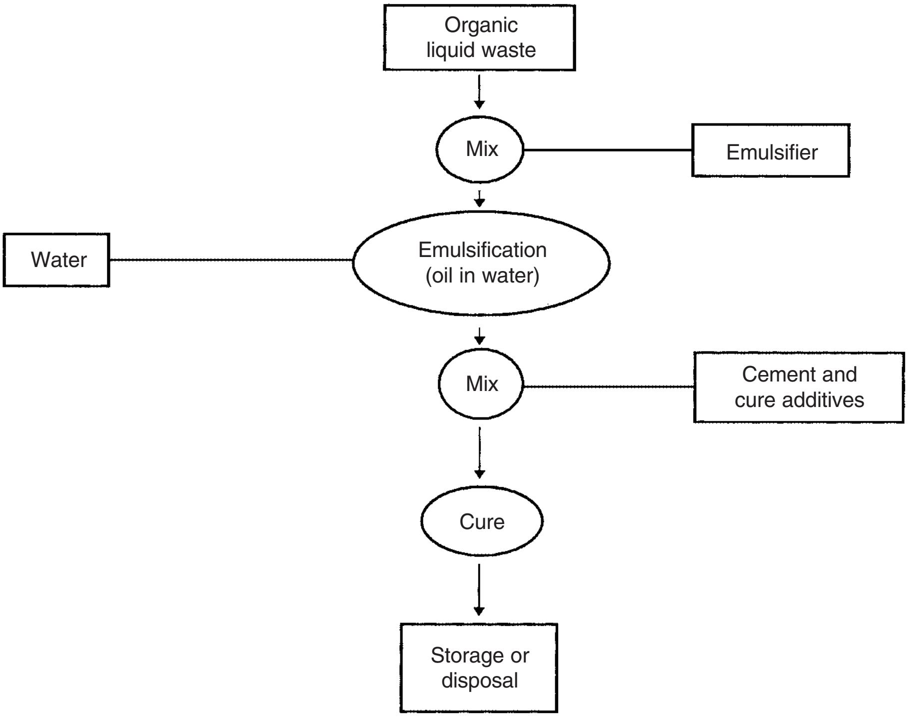


FIG. 20. Flow diagram of organic liquid waste solidification using cement.

Cementation has been used extensively in the USA to solidify waste turbine oil, pump oils and TBP/dodecane solvents [64].

A typical composition for radioactive oil solidification in a 200 L waste form would be [65]:

— 165 kg of Portland cement,
— 17 kg of lime,
— 72 L of oil,
— 62 L of emulsifier,
— 14 L of water,
— 7 L of silicate accelerator.

The cement and lime should be dry mixed thoroughly in a waste container. The oil and emulsifier should be mixed in a separate container; water should then be added and the components mixed to form an oil in water emulsion. The emulsion should then be added to the cement/lime powder and the whole stirred until the batch is homogeneous. The silicate cure accelerator is then added and stirring continued for a short time to ensure uniform dispersion of the accelerator. The mixer can then be removed and the container closed and stored for product cure to take place. Typically, adequate cure for transport to the interim storage/disposal site will require 4 to 28 days.

Although cementation is a simple process requiring only rudimentary equipment, it is important to note that the degree of cure and resultant waste form integrity can be adversely affected by minor compositional changes in the waste feed. Thus it is essential that small sample solidification tests be done on each batch of waste before full scale solidification. These determine whether formulation modification is necessary to obtain the desired waste form.

10.2.3. Combined processes

Often, substantial advantages can be accrued by selecting a combination of two or more processes, rather than a single process, for treating organic waste. For example, instead of emulsifying the organic liquid waste before introducing it to the cement powder, this approach converts the organic liquid into a dry particle form that is then mixed with the cement powder and water to produce the final waste form [64]. The advantages of this technique are that the procedure is more tolerant of batch to batch waste variability and that higher waste loadings, of up to 56 vol. % organic liquid, can be attained. A disadvantage is the need to convert the organic liquid waste to a dry solid before adding it to the solidification matrix. Figures 6 to 8 suggest some possible process combinations for treating scintillation liquids and miscellaneous solvents, oils and solvent extraction wastes, respectively. Some of the advantages and disadvantages of each combination are also presented.

Some typical compositions of solidified waste forms using this technique are given in Table XXVIII.

TABLE XXVIII. OIL WASTE SOLIDIFICATION WITH ABSORBENTS AND CEMENT

Absorbent	Cement (g)	Oil (g)	Absorbent (g)	Water (g)	Liquid waste content (vol. %)
Clay	200	32.20	71	71	15.60
Vermiculite	200	84.00	24	120	21.80
Natural fibres	200	321.00	11	70	56.00
Diatomaceous earth	200	372.00	265	160	38.75
Synthetic fibres	200	295.00	34	165	44.50

If the organic liquid waste is contaminated with water, it may be possible to reduce the amount of added water given in Table XXVIII by a similar amount to that contained in the waste feed. However, it is important that the mix should contain enough water to hydrate the cement adequately, otherwise the solidified waste form may not have sufficient integrity.

This technique, as for simple cementation, is a low cost process requiring minimal operator skills and cheap, readily obtained equipment. Even the increase in volume of waste resulting from this process may not be a disadvantage where only small volumes of organic liquid waste are expected to arise.

10.3. CONDITIONING OF BIOLOGICAL WASTE AND ANIMAL CARCASSES

Animal carcasses, organs and similar biological waste arisings present special needs for conditioning prior to long term storage or disposal. Research staff and other generators should be strongly encouraged to minimize the use of animals, owing to the difficulty of managing this type of waste and on humanitarian grounds. Using short lived radionuclides for animal experiments allows their wastes to be frozen for decay storage, with eventual disposal as non-radioactive material. For animals contaminated with long lived radionuclides, where neither decay storage nor incineration are appropriate (for example in the event of very infrequent experiments requiring long lived radioisotopes), then immobilization in a cement grout may be used [10].

For larger animals the carcass should be first treated to halt putrefaction by immersion in a container of 4% formaldehyde and being left to bathe in the solution for a minimum period of two days. It is important that formaldehyde is used in an area with a fume exhaust ventilation system, owing to the carcinogenic potential of this liquid. The volume of the container of formaldehyde should be approximately twice the volume of the animal carcass. The animal carcass should be removed and drained of excess liquid before being immobilized with cement grout. The animal can then be loaded into a container and the voids filled by a flow of fluid cement slurry or grout. Vibration should be used to ensure good a penetration of cement around the waste. This technique is not recommended for frequent use as it is cumbersome, increases the waste volume considerably and the formaldehyde solution, which may also be contaminated with radioactivity, will require disposal as chemically hazardous radioactive waste.

Small animal carcasses and similar biological materials can be directly immobilized in a cement matrix (Fig. 21). Two drums of different capacity should be used. The inner drum should be about 25 to 60 L and the outer drum about 220 L. The inner drum should be prepared by creating a 50 mm concrete layer at the bottom. Dry cement should then be poured to obtain a 20 mm layer. The unpackaged frozen carcasses should then be placed in the drum. Dry cement should continue to be

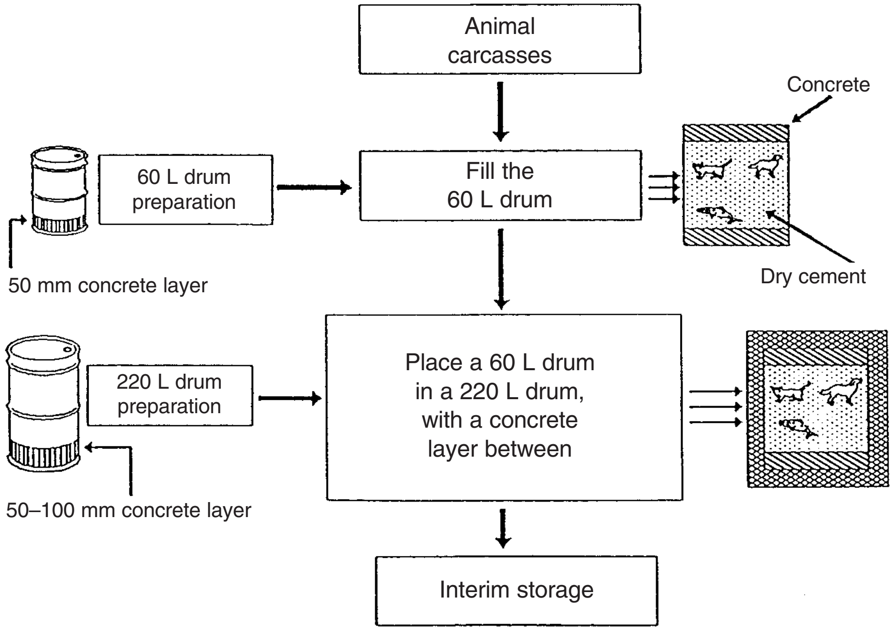


FIG. 21. Flow diagram for conditioning animal carcasses.

poured until the carcasses are completely covered. This operation should continue until the top is almost reached, leaving sufficient space to create another 50 mm concrete layer at the top of the drum. This drum should be inserted into an outer (approximately 220 L) drum prepared with a 50 to 100 mm concrete layer at the bottom. The drum should not be hermetically sealed in order to permit the release of gases resulting from the putrefaction process. Adequate exhaust ventilation and environmental monitoring will be required where gaseous releases of ^{3}H, ^{14}C or ^{35}S emanate from the putrefying waste. The inclusion of an absorbing agent to surround the animal carcasses (for example vermiculite or polystyrene foam), which is then incorporated into the cement matrix, is recommended. This traps the organic liquids that seep from the carcasses, which could result in the cement rapidly deteriorating [10].

The main reasons for using a cement grout to immobilize animal carcasses and other biological radioactive materials are:

— The relative simplicity of handling and availability of raw materials,
— The relatively low cost,
— The high density (shielding) and mechanical strength of the products,
— The compatibility of water with the matrix material.

10.4. CONDITIONING OF NON-COMBUSTIBLE, NON-COMPACTIBLE WASTE

Non-combustible, non-compactible waste often requires special treatment, depending on its particular characteristics. Those wastes contaminated with long lived radioisotopes, such as sealed sources, should be immobilized prior to their storage and disposal [30, 31]. Figure 22 shows the various steps involved in the conditioning of non-compactible waste. Radioactive solid waste should be loaded in an appropriate container and the voids filled by a flow of fluid cement slurry or other grouting material. Vibration should be used to ensure a good penetration of the grout and complete encapsulation of the waste within the container.

Traditionally, cement grouts have been used or recommended as the most suitable material for conditioning radioactive non-compactible waste. The grouts are commonly of neat cement with or without the addition of a fluidizing agent, but sometimes finely ground aggregates, such as sand, slag or ash, are added. It is important that the grout should have good flow characteristics and be relatively free from free water. The water to cement ratio of the grout should be varied according to the resistance to the passage of the grout, and can vary from 0.4 to 1.0. The main reasons for using cement grouts are:

- The relative simplicity of handling,
- The availability of the raw material,
- The low cost.

Preparation of cement grouts or concretes can be accomplished through the use of a simple cement mixer, as shown in Fig. 22. Non-compactible waste, such as contaminated metal, glassware and equipment packed into drums or containers, can easily be immobilized by pouring cement grout into the container.

Various non-ferrous metals and alloys can be attacked by the alkaline solutions present in damp or wet Portland cement grouts and concretes. For example, aluminium, zinc and zirconium react with alkali hydroxide solutions and produce hydrogen. Lead and ferrous bearing metals form a protective oxide film over themselves, causing expansion, cracking and deterioration of the concrete. In some cases this may cause the container to break, thus making it more susceptible to water intrusion and leaching. Where this problem is anticipated, it may be necessary to coat the metal with a butiminous or polymer material prior to introducing the cement grout [5]. These coating materials can form strong bonds with metallic materials, which minimize shrinkage or delamination, and forms an impermeable barrier to water intrusion.

An alternative solution may be to use a polymer based grout, such as molten polyethylene, sulphur cement or bitumen. Where fluidity is important, liquid

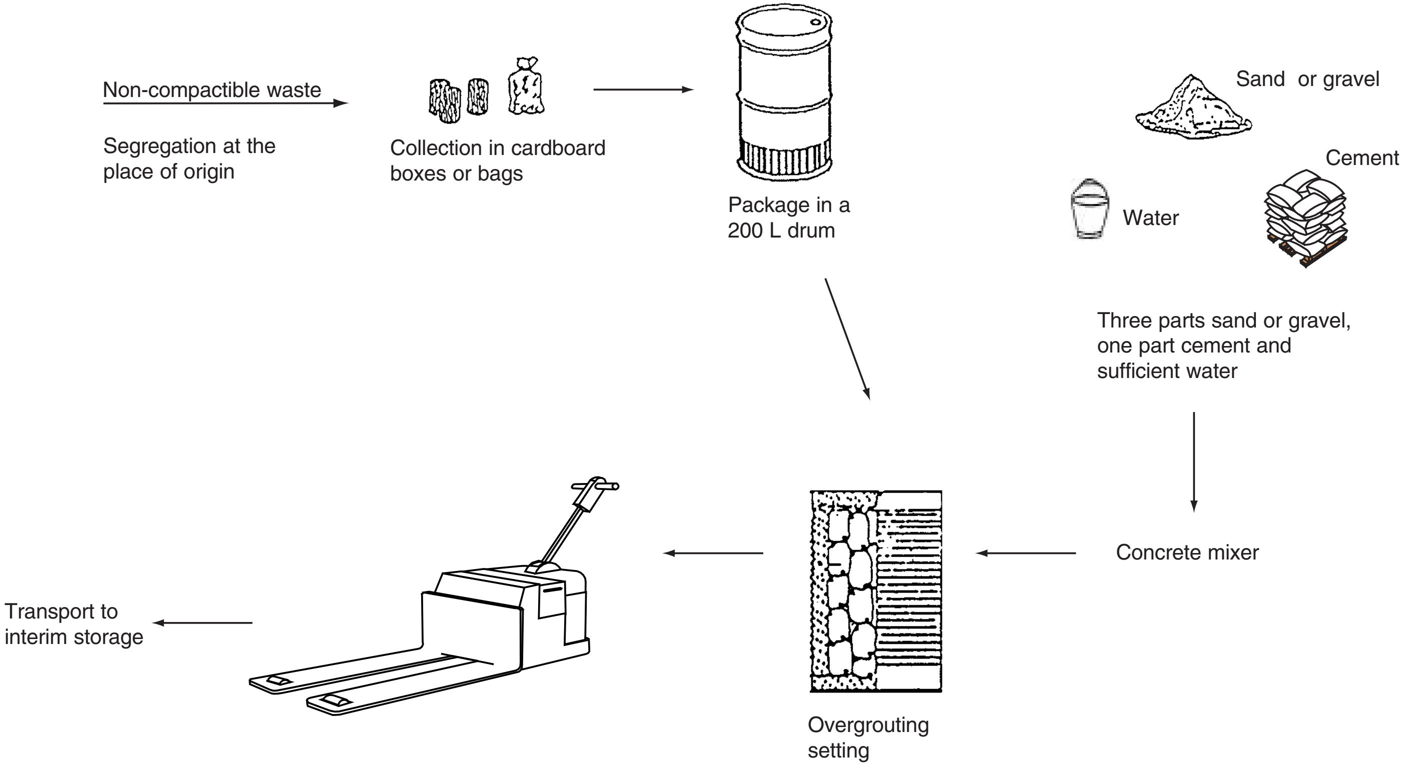


FIG. 22. *Conditioning of non-compactible radioactive solid waste.*

monomeric systems capable of polymerizing in situ, such as unsaturated polyester styrenes and epoxies, can be used. Although organic polymers have exhibited more desirable physical and chemical properties than cement for use in conditioning waste, their use is limited owing to their costs being higher than those for inorganic materials.

11. PACKAGING

Typically, carbon steel drums of at least 200 L are the waste containers used for immobilizing liquid and wet solid wastes. Little use is made of concrete drums, primarily because their added weight and thickness requirements may affect their volumetric efficiency.

The primary purpose of a container is to provide integrity for a waste package during handling, interim storage, transportation and disposal. In most cases it also serves as the vessel used during solidification.

Depending on the materials being shipped (the types of radionuclides and their gross activities), transport regulations may require that waste packages have either protective overpacks or inner linings to provide additional mechanical integrity and/or radiation shielding.

The following general guidelines should be considered in selecting a suitable container.

- All packaging should provide at least two independent barriers designed to contain radioactive materials throughout handling, transport and storage/disposal operations (e.g. waste immobilization and containerization);
- The container should be small enough in volume and light enough in weight to be easily handled by conventional handling equipment, and be of a uniform shape;
- The container should be watertight and capable of resisting the storage/disposal environment;
- The container should have sufficient structural strength to withstand stacking, dropping and penetration tests, and meet the shipping criteria for transportation to a storage/disposal site without the requirement for the waste to be repackaged.

It is anticipated that in most cases developing countries will select a standard 200 L drum because it is:

- Readily available at low cost,

— Easily handled by conventional equipment,
— Acceptable as a type A (as defined in Ref. [66]) container for transportation.

Figure 23 shows a container that can be used for packaging radioactive waste generated at various nuclear facilities. Depending on the level of activity, other containers are also commonly used. Some of their characteristics are given in Table XXIX [67]. Additional information on other containers can be found in Ref. [67].

12. STORAGE OF CONDITIONED WASTE

The interim storage of conditioned waste during the interval between processing and the establishment of a final disposal repository in most developing countries is likely to be long term (up to 50 years). Only conditioned solids in selected containers are suitable for such lengthy storage. Liquids, which are potentially more mobile, and hence more difficult to isolate from the environment, should first be immobilized.

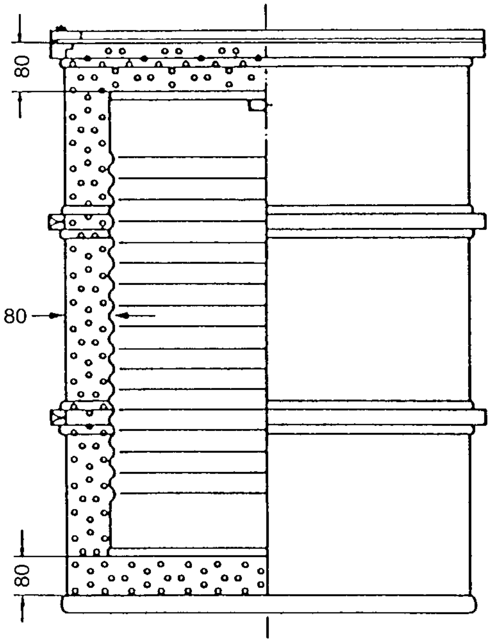


FIG. 23. Two steel drums, the inner one surrounded by a concrete lining.

TABLE XXIX. CHARACTERISTICS OF SOME COMMON CONTAINERS IN USE

	Type of container			
Property	200 L drum	200 L drum surrounded by concrete inside a 400 L drum	Concrete container with a 200 L drum inside	Cubical concrete container
Inner volume	200 L	200 L	200 L	1000 L
Outer volume	200 L	400 L	1000 L	1740 L
Dimensions (outside)	Diameter, 57 cm; height, 88cm	Diameter, 77 cm; height, 110 cm	Diameter, 100 cm; height, 125 cm	Side length, 1200 cm
Loaded weight	200–500 kg		Up to 2.5 t	Up to 5 t
Wall thickness	1 mm	10 cm	20 cm	10.25 cm
Material	Mild steel	Mild steel, concrete	Normal concrete and mild steel	Reinforced normal concrete
Coating	Paint	Paint	No	No
Closure	Ring	Ring	Concrete cap	Concrete cap
Biological shield	None	Concrete	Concrete	Concrete
Strengthening	Iron bars	Iron hoops	Iron bars	Iron bars
Mechanical property	Good	Very good	Very good	Very good
Ease of handling	Good	Good	Good	Good
Ease of decontamination	Good	Good	Poor	Poor
Corrosion restistance in				
Air	>10 a	>100 a	>100 a	>100 a
Fresh water	>10 a	>100 a	>100 a	>100 a
Saline water	>10 a	>100 a	>100 a	>100 a

12.1. GENERAL REQUIREMENTS

Two hundred litre steel drums are the generally recommended containers for storing conditioned solid waste (type A packages). Such drums are commercially available from a number of suppliers. Depending on the level of activity, other containers are also commonly used; their characteristics are given in Table XXIX. It is likely that only a few of these alternative containers will be used in class A, B and C countries, possibly for some of the larger spent sealed sources or some larger contaminated metallic or other scrap. Ad hoc arrangements could be made for the larger shielded containers, if required.

Conditioned waste should be acceptable for long term storage and/or disposal. Cementation is appropriate for conditioning waste containing long lived radionuclides such as precipitation sludges and spent ion exchange media. In-drum compaction is appropriate for solid compressible waste, and in some cases cement grouting may be used to embed compacted waste. A storage facility must, therefore, be designed to accommodate all these waste forms. If other waste forms, such as bitumen or polymer immobilized wastes, are produced in the country, then the facility design must take these into account.

The storage facility should be designed to handle the volume of waste to be produced during the planned period of operation. On the supposition that the generation of radioactive waste in a small nuclear research centre will be approximately constant over ten years, the estimated volume of conditioned waste after this period is in the range of 150 to 300 m^3, corresponding to 750 to 1500 (200 L) drums.

Other general considerations for a storage facility are security and fire protection. A radioactive waste storage facility should be well protected against unauthorized human intrusion. It should be constructed, operated and maintained in such a way that unauthorized removal of radioactive waste is prevented. An adequate locking mechanism should be provided to prevent unauthorized access, and it is recommended that physical barriers, including fencing and an intruder alarm system, be installed. Should intrusion occur, security arrangements should ensure that any unauthorized removal of waste is prevented, or promptly discovered and effective measures initiated to recover the missing material.

When assessing the overall safety of a radioactive waste storage facility it is necessary to consider the possible consequences of an accidental fire, and steps should be taken to minimize its risk. The careful selection of non-flammable construction materials when building a storage facility will greatly reduce this hazard. A storage facility should not be used to house any highly flammable or highly reactive materials.

Liaison with local fire fighting authorities is necessary. Their advice should be sought regarding provision of fire fighting equipment in the vicinity of a waste store.

If a conditioned waste storage building is also used to store unconditioned waste, the two waste types should be separated, especially when storing unconditioned flammable liquids such as scintillation fluids.

12.2. DESIGN FEATURES

A variety of conditioned waste storage concepts are used in waste management programmes. These depend on a number of factors, including:

- The nature and activity of the conditioned waste,
- The package size and shape,
- The package handling requirements,
- The volume of waste for storage,
- The period of storage,
- The need for future store expansion,
- The local site factors (i.e. weather and land conditions),
- Other country specific factors.

Designs can be divided into two categories: area storage or engineered storage. Area storage involves standing waste packages on the ground, in the open or with a simple covering. Area storage is not generally suitable for the lengthy storage periods required for developing countries.

Many engineered storage designs are based on those used in nuclear fuel cycle facilities, which need to handle large volumes of drummed or boxed encapsulated waste packages with high surface dose rates, and as such are unnecessarily sophisticated for the low active waste arising from the institutional activities of developing countries.

Simple engineered storage designs matched with simple mechanical handling by a forklift truck, with storage capacity for at least ten years, should be considered. The need for retrievability should be restricted to the one occasion in the future when the waste is moved to a disposal facility. Storage of waste containers should be arranged by stacking them in rows several levels high, as shown in Fig. 24.

Interim storage of conditioned waste in Member States with a small nuclear research centre could be within a simple hall at ground level, with a steel construction and corrugated transit sheets covering the walls and the roof. The storage hall should be built above the groundwater level and be out of reach of a potential flood or groundwater. Where this is not possible, the building must be constructed with appropriate protective systems to prevent the ingress of groundwater. The capacity for a waste storage facility should be designed for a period of ten years or more, depending on the volumes and types of waste being stored.

FIG. 24. Typical stacking of waste drums.

In the reference design of a waste processing and storage facility [1], the store is a single storey rectangular building with overall plan dimensions of approximately 39 × 26 m, rising to an eaves height of approximately 4 to 5 m. The roof is of a symmetrical double pitch form. The building size and form is designed to facilitate the storage of 3000 waste drums and to ensure that it may be extended in the future, to increase its drum storage capacity, without the need for structural modifications to the original building.

The building is of a steel frame construction, which is preferred over a wood frame for fire hazard control reasons. Unbraced, three bay, portal frames are provided at approximately every 4.3 m along the length of the building. These portals provide support to the roof structure and lateral stability for the building in the transverse direction. Stability of the building in the longitudinal direction is provided by a system of roof bracing and bracing to the longitudinal external building elevations, which ensures that all lateral loads at the roof level are transmitted to the foundations.

The exterior walls are comprised of commercially available uninsulated metal cladding on steel sheeting rails that span horizontally between the perimeter stanchions. Although not always necessary, consideration may be given to the possible future option of providing an inner shield wall. This could be of a concrete block or reinforced concrete construction and be located between the perimeter stanchions to which it would be mechanically tied. The overall building width takes into account the space requirements for the construction of such a wall, assuming the waste drums are in place and adequate wall foundations have been provided. Internal partitions are not provided. The stanchions are founded on individual concrete bases at a suitable soil bearing position.

The ground floor is comprised of a reinforced concrete ground bearing slab. This slab is thickened locally all around the building perimeter (to support the future shield wall) and locally around all internal stanchions. Resistance to water penetration from the ground is provided by a polythene damp proof membrane on the underside of the slab. The ground floor slab is finished with an epoxy paint.

Structural steelwork generally is grit blast cleaned and treated with a zinc rich primer followed by an alkyd undercoat and gloss finish paint system. All sheeting rails and purlins are hot dip galvanized.

Future extension of the building may be achieved by the addition of further pantal bay frames, thus increasing the length of the building in 4.3 m modules. The only modifications to the existing building made necessary by such an extension is the removal of sheeting, sheeting rails and sheeting posts to the end gable to enable access between the existing and extension areas. The general safety design features for storing unconditioned waste in buildings (see Section 5) are all generally applicable to storing conditioned waste.

12.3. MATERIALS HANDLING

Solid waste accepted for a conditioned waste store will have previously passed through some type of waste treatment plant where the opportunity existed to standardize on a single waste package type. As noted earlier, in most cases 200 L drums are advisable as the standard package. Further, it is anticipated that in the majority of circumstances the waste package will not require shielding, the external waste package surfaces will be clean and uncontaminated, and individual waste packages could weigh up to 500 kg.

Handling equipment will need to be compatible with the store design and the waste package characteristics, in particular the radiation levels. It is expected that an industrial forklift truck with a drum grab attachment will be the most suitable method for handling this type of waste package and placing it into the interim storage facility. In some cases more than one drum can be handled at a time on a pallet or drum rack.

Building cranes are used in many intermediate level waste stores in developed Member States, particularly when there is a need for remote handling of waste packages. These overhead cranes are expensive to install and usually require a facility of complex construction to support the crane structure. Because of high costs, and because it is expected that remote handling of conditioned waste in most cases will not be necessary, building cranes are not justifiable for use in conditioned waste storage facilities for developing Member States.

12.4. OPERATING PROCEDURES

The control of operations in an interim storage facility for conditioned waste is likely to be less complicated than in the facilities described for a variety of unconditioned wastes (Section 5.5).

Waste should normally be received on a regular schedule based on the output of the conditioning facility. It should be nearly uniform, well packed, robust and in intrinsically safe containers. The interim storage objective is essentially passive for the long period pending removal (probably in bulk) when a disposal repository is established.

The operating details for the receipt, storage and dispatch phases considered earlier for unconditioned waste stores generally apply. However, the protracted period of operation makes necessary near permanent markings on the containers and records of their contents and locations. Segregation of waste types is desirable to aid any retrieval, which might be required if a periodic inspection reveals degradation of their containers or if different categories of waste are to be placed in separate disposal repository locations.

The radionuclide content in conditioned waste must comply with the local regulatory limits. The acceptable radiation dose rate emitted by conditioned waste packages is limited by the permitted radiation exposure level to personnel. Typically, if the dose rate at 1 m is less than 0.5 mSv/h direct contact handling is acceptable, otherwise radiation protection features such as shielding or remote handling are mandatory.

A maximum allowable dose rate at the surface of each waste package should be defined for specific interim storage buildings or parts of buildings, for:

- Low level storage with access by a manual system,
- Shielded intermediate level storage with access by remote and automatic devices.

In some cases low dose rate drums can be placed around those with higher dose rates to provide some shielding. Package acceptance criteria are discussed in more detail in Section 13.2.

Measurements may be performed on each completed package to determine its radiological characteristics. Waste package identification should ensure that each waste package is uniquely identified from the time of production. Marking and labelling should be performed according to local regulations and adequate traceability of waste packages should be established.

12.5. SAFETY ASSESSMENT

Formal safety case reporting is generally carried out at a late stage of the design for low level waste storage facilities owing to their low activity inventories and low ranking for risk. The very rigorous safety analyses carried out for some nuclear fuel cycle facilities are unlikely to be required. However, the degree and timing of the safety assessment required depends on individual national regulatory requirements.

While stores contain the largest inventories of activities, the operations undertaken in them do not pose a high hazard with respect to the difficulties in containment or isolation of the radioactivity from the work or external environment during normal or abnormal conditions. Rapid changes from safe to harmful conditions are unlikely in the storage of conditioned waste.

Predisposal storage is an option available in any waste management strategy. Any facility chosen as part of this strategy should have acceptable radiological protection. The designs proposed should follow the general principles of keeping dose levels ALARA and reducing the probability of accidents to as small as practicable. In addition, the design should be capable of maintaining the ‘as received’ integrity of waste packages until they are retrieved for disposal. These principles, when incorporated into a sound and well engineered design constructed and operated to acceptable standards, are the basis for limiting the radiological impact of a storage facility.

Radiological safety should be addressed qualitatively, and an initial assessment should be a preliminary overview of the safety concepts. From this assessment sensitive areas of the facility design, package design and/or operating system should be identified. It is these areas that will have a priority for a quantitative assessment.

The assessed safety of the facility should be a reflection of its inherent susceptibility to hazards as well as the degree to which such hazards can be avoided or contained. In this context hazard refers to a situation whereby persons may become exposed to radiation or to airborne contamination, either inside or outside the facility.

The assessment approach thus includes identifying hazards and examining the protection or mitigating features. Hazard potential refers to the presence of radioactive substances in the waste packages being stored or handled. Specific hazards should be identified by examining the various operational or non-design circumstances whereby exposure to radiation or to airborne contamination may occur.

Significant hazards should be avoided by the provision of design features or administrative measures. The extent to which this objective has been achieved needs to be determined. Design features of interest may include radiation shielding, remote handling or monitoring devices, maintenance aids, ventilation/filtration systems and containment barriers Administrative measures may include operating, maintenance and health physics procedures.

In the type of rigorous assessment that may be used in the approval process, hazards may be quantified in terms of their frequency of occurrence and the magnitude of their consequences. The effectiveness of protection or mitigating features may then be similarly quantified in terms of the reduction of the risk associated with each hazard. It should be noted that regulatory agencies in many countries have additional specific requirements for safety case assessments of waste management facilities that must be addressed. Both normal and abnormal operating circumstances should be considered.

12.5.1. Normal operation

Hazardous situations may arise that might affect:

- The operating and maintenance staff performing their usual duties,
- Other people in the vicinity of the storage facility.

Direct radiation, and possibly airborne contamination, are of concern, and an assessment must take account of the normal situation both inside and outside a facility. The outline procedure may be summarized as follows:

- Identify all potential radiation or contamination sources and the expected accumulation of these during the operational lifetime of the facility;
- Identify operating staff movements within the facility;
- Identify routine maintenance activities;
- Assess the radiological hazard to operating and maintenance staff;
- Identify the radiation field external to the facility;
- Identify any routine releases of radioactive substances to the environment;
- Assess the radiological hazard to people outside the facility;
- Identify and assess those protection or mitigation features that may affect any radiological hazards;
- Assess conventional safety hazards such as falling drums, fumes and fire.

12.5.2. Abnormal operation

Abnormal operation occurs when events lead to faults within a facility. Depending upon the extent of the fault, its influence may be limited in safety terms to the operating and maintenance staff or may extend to the outside environment. For each event it is necessary to determine the resulting hazard. This depends on:

- Faults resulting from initiating events: these may be of internal or external origin.

  - Internal events may include malfunctions or mal-operations during the handling of waste packages, fires or floods from internal causes.
  - External events may include earthquakes, impact (e.g. a vehicle or airplane crash), fires or floods from external locations.
- The extent to which radiological barriers (shielding or containment) are degraded; such barriers may be part of the waste packages themselves or be part of the facility.
- Any resulting change in the radiation field and/or dispersion of radioactive substances inside or outside the facility.
- Any consequential deviation from normal operating or maintenance practices that cause abnormal exposures to the staff.

The outline assessment procedure for an abnormal event may be summarized as follows:

- Identify the initiating events to be considered.
- For each event characterize the resulting fault; that is, identify the effects of the fault and the response of the facility.
- Determine the severity of each fault and categorize it as an incident or accident.
- Group incidents and accidents as appropriate and assess the radiological hazards to operating and maintenance staff and to people outside the facility.
- Identify and assess those protection or mitigation features that affect the radiological hazards.

Faults that could give rise to hazards in a store include:

- The dispatch of an externally contaminated drum to the store,
- A drum dropped while being moved,
- The failure of containment during storage.

Following immobilization and curing, each drum should have been checked for contamination prior to dispatch to the store. Failure to do this may result in the spread of contamination both in the facility and the store, which may result in an increased risk to the workforce handling the drums and require extensive decontamination of the store before operations can recommence. Contamination of the drum can result from the failure of a seal or sealing mechanism, overfilling of the drum or failure of the inspection system.

Following drums of immobilized waste being dropped, the release of activity into a work area will be low since the activity in the waste will be only dispersible with difficulty. In addition, the heights that loads can fall are restricted as the building will have only a single storey and the drums should be stacked only three high.

Another hazard for a storage facility arises from the degradation or failure of the drum containment. This could occur if sub-standard drums (i.e. because of a manufacturing fault) are used, from damage to a drum after filling, or corrosion or erosion in long term storage (either internally or from external condensation). The risk from this hazard is very low, however, since the low mobility of the activity minimizes any airborne contamination problems.

13. QUALITY ASSURANCE

Quality assurance (QA) is an essential aspect for the good management of radioactive waste. QA includes all planned and systematic actions necessary to provide adequate confidence that an item, process or service will satisfy given requirements and specifications. Compliance with a QA programme thus provides confidence that the objectives of waste management are being met, as detailed in the appropriate specifications for waste processing, packaging and storage operations.

13.1. QA REQUIREMENTS AND PROGRAMME

A QA programme defines the organization, responsibilities, relevant performance standards and steps, and organizational interfaces involved in a waste management process. It also provides for a system of document control and records to demonstrate that the required quality has been achieved, and initiates corrective action where it does not. General guidance for establishing a waste management QA programme can be found in Refs [69–73].

13.1.1. QA requirements

The intrinsic and desired properties that need to be quantified, monitored or otherwise assured have to be assessed for each step of an overall waste management scheme. For handling, transport and storage operations the requirements mainly concern the safety of operators, security of waste from interference or theft and behaviour of packaging under possible abnormal conditions.

The QA programme objective in waste management involves three components:

- The intrinsic quality of the process;

- The rigorous implementation of process requirements so as to guarantee the optimum quality of a product;
- The control of the end product or end situation so as to assure conformity between the quality and composition of the end product, including the non-radioactive components, and the agreed standards and criteria.

QA for the centralized management of low level radioactive waste from nuclear institutions should therefore be inherent in the design of the overall management strategy, in the controls placed on each step of the execution of that strategy and in the system for documenting this performance. Assurance of quality should not have to rely on exhaustively checking the conditioned product [73].

It is clear that QA programmes and audits will be different for centralized and decentralized strategies. Greater incentives for a comprehensive programme may be associated with a centralized strategy, but it is essential that appropriate QA is applied in a decentralized system, where maintaining standards may be more difficult owing to the variety of activities and limited resources.

The IAEA recognizes that guidance on a QA programme for radioactive waste should be given to the competent national authorities as well as to the individuals and organizations directly involved in managing the waste. However, the basic responsibility for achieving quality in performing a particular task rests with those assigned that task, not with those seeking to ensure, by means of regulation, that it has been achieved.

13.1.2. QA programme

A QA programme should be developed by the licensee/operator to define and describe the relevant steps of the waste management process. It should also describe the interface arrangements with the various groups or organizations involved in waste handling, treatment and storage needed in order to achieve compliance with the relevant standards and requirements. Radiological and other hazards and personnel safety must be considered. It also should provide for the production of documentary evidence to demonstrate that the required quality of processes and products has been achieved. The details of a QA programme should be commensurate with the extent and complexity of the activities giving rise to the waste and to its quantities and potential hazards.

The objective of a QA programme for centralized radioactive waste management is to provide adequate confidence that:

- The facilities and equipment are designed, procured, constructed, commissioned and operated in accordance with the specified requirements for safe operation;

- The waste packages produced are handled, stored and transported in accordance with the specified requirements in full compliance with national legislation;
- Waste acceptance criteria are met;
- All regulations and conditions in any licence or authorization are complied with;
- Waste is bulked and decay stored as required to optimize the use of available disposal routes, hence providing a cost effective operation that causes the least detriment to the environment.

For waste management operations the following topics should be covered by a QA programme:

- Its purpose and scope (including a statement of commitment from top management);
- The organization (including the identification and control of interfaces);
- Staff training and qualification;
- Document control;
- Design control (including plant modifications);
- Procurement control (i.e. waste containers and any materials used in the waste conditioning process itself);
- Materials control;
- The initial qualification of the plant, the process and the waste package;
- Product quality verification;
- Important data records;
- Assessments and audits;
- Management review and signoff at fixed time intervals and prior to changes to the documented processes;
- Non-conformance and corrective actions.

In the case of predisposal waste management a QA programme should focus on:

- The minimization and segregation concepts for the waste arisings;
- Accurate and complete documentation of the waste at the points of generation;
- The waste acceptance criteria of the treatment facility;
- The requirements for conditioned waste (the waste forms to be produced, the conditioning techniques and plants, testing and documentation);
- The quality requirements for waste packages;
- A description of the control and measuring methods;
- A documentation system that covers the required records;

- The organization that ensures the implementation of the QA programme;
- Non-conformance and corrective actions;
- Audits;
- Programme reviews.

In addition, a predisposal waste management QA programme should be integrated with a disposal QA programme, as outlined in Ref. [71].

13.2. ACCEPTANCE CRITERIA FOR WASTE PACKAGES

Waste acceptance criteria are derived from the safety analyses and operational requirements for transportation and from performance assessments of the disposal facility. It is the responsibility of the transport package licensee and the repository or disposal facility operator to develop waste acceptance criteria and to varify compliance of the waste that is accepted for transportation or for disposal. The waste acceptance criteria may be drawn up under guidance and/or with the approval of the regulatory bodies. Interim storage facilities designed for long term monitored retrievable storage may also issue waste acceptance criteria.

Individual waste management organizations (e.g. waste producers and waste processing facilities) themselves frequently develop waste specifications to confirm or control the radiological, physical and chemical characteristics of the waste to be produced, processed or accepted from another organization.

Waste acceptance criteria are used to identify, control and document the type and quantity of the radioactivity, as well as the physical handling and long term stability of the waste. General qualitative acceptance criteria for waste packages consigned to a low level waste repository should cover:

- The radionuclide inventory;
- Radiation levels (dose rate);
- Mechanical properties;
- Chemical durability;
- Gas generation;
- Combustibility and thermal resistance;
- Limiting or avoiding free liquids, explosive and pyrophoric materials, compressed gases, toxic and corrosive materials;
- Physical dimensions and weights;
- Unique identifications;
- Responsibilities and organizations;
- Compliance with codes, standards and national regulations.

These requirements have been presented and discussed in Refs [28, 71, 73]. In many countries specific quantitative limits are applied to some or all of the above criteria.

The waste acceptance criteria for waste packages in storage include:

- The maximum allowable weight per package,
- The mechanical resistance of the packages to be stacked,
- Satisfactory corrosion resistance of the package metal,
- No loss of integrity after a test drop from a height equivalent to that found during transportation,
- Sufficient resistance to a standard fire test.

These criteria or limits are set to ensure that waste packages will still be in an acceptable physical condition for their safe retrieval and handling when they are moved to the next step in the waste management scheme (e.g. from storage to disposal). Some limits, such as the radiation dose rate, are mainly of concern for immediate handling (since the dose rate will be reduced over time), while others have a longer term impact, such as gas generation that may result in a fire or explosion years in the future. Additional guidance on waste form acceptance testing can be found in Ref. [74].

13.3. SYSTEM REQUIREMENTS

An operator's organizational structure should provide sufficient independence for a QA function. The responsibilities and authority of the personnel and organizations involved should be clearly delineated. QA should apply to all radioactive waste management activities, especially those features important to safety. In particular, a QA programme should ensure that waste packages meet the waste acceptance requirements.

A regulatory body should review the QA programme of an operator and may identify QA measures that have to be carried out independently of the operator.

Where the long term performance of a system cannot be proved by direct observation, a research and development programme should be established to obtain the necessary information. Such a programme may be carried out in co-operation with international research and development programmes.

Lessons learned from national and international operating experience and research need to be considered by both the operating organization and the regulatory body in order to determine whether equipment, training or related safety requirements need to be modified.

13.4. RECORD KEEPING

The preparation and maintenance of a comprehensive system for record keeping is essential. The need for recording specific information regarding the waste arising, and its subsequent handling, treatment and storage, as well as the labelling of individual waste packages, has been described in Sections 5 and 12. In addition, it is likely that there will be local regulations governing the records that are required to be kept. Records should be clear, legible, permanent and maintained up to date at all times, such that they are readily available for inspection. It is suggested that the record keeping system be computerized. Multiple copies of the records or access to the database by several agencies may be required.

A documentation system should provide an integrated record of the waste from the time of its production, through all of its handling and treatment stages, through to storage and final disposal. The system should be able to identify and track any individual package. A record of the final disposition of the waste must be maintained for an indefinite period.

The following information should be included on the labels on individual packages and entered into a system of clear, permanent, legible records:

- The package number;
- An informative description of the waste;
- The details of its origin;
- Its physical, biological and chemical characteristics;
- Its radionuclide inventory;
- Its radiation level;
- The package volume and weight;
- Details of other specific hazards, such as whether it is infectious or chemically hazardous;
- Further details relevant to additional treatments necessary before the waste is sent for storage or final disposal;
- The name/signature of the person responsible.

Arrangements for the collection of radioactive waste packages should reflect the nature and quantity of the waste to be collected.

The exact format and level of detail required should be documented in the waste acceptance criteria (see Section 13.2) of the waste management facility. The documentation system should also record the package number and its current status (e.g. storage location and treatment date). The information recorded enables the waste to be tracked, handled, processed, stored and disposed of safely. Proper long term maintenance of records is required.

Only authorized individuals should be allowed access to the record system or database. The system must be designed to resist tampering or alteration and should provide appropriate backup or redundancy to assure that data will not be lost owing to accidents or unexpected events. The QA programme should provide for the controlled approval, receipt, retention, retrieval, distribution and disposition of all records.

13.5. AUDITS

The implementation and effectiveness of a QA programme should be verified through an auditing process. In general, it is appropriate to place audits into four categories:

(a) System audits,
(b) Process audits,
(c) Product audits,
(d) Waste producer audits.

13.5.1. System audits

System audits should:

- Verify that a programme and plan address the applicable requirements,
- Verify that a programme and plan's requirements are adequately addressed in the implementation procedures,
- Verify that implementation is adequate and identify deficiencies and non-conformities,
- Recommend corrective action,
- Provide management/regulators with an assessment of the status and adequacy of a QA programme.

13.5.2. Process audits

Process audits are necessary to verify that the processes are being operated within the specified boundaries fixed during the course of process qualification and that hardware is being controlled in a manner that meets its design requirements. Normally, determination of compliance to process requirements should be built into a QA programme as quality control or verification activities performed by the organization operating the process. A system audit should confirm that the verification is being performed. Process audits may become the responsibility of the waste management organization when the waste producer lacks the infrastructure to perform the quality control functions.

Process audits should focus on:

- Assuring that important process variables have not changed from those values established in the original process qualification,
- Assuring that required inspections and measurements are performed and that records are retained,
- Verifying that traceability is maintained during the transfer of waste and during interim storage,
- Assuring that instrumentation used to monitor or control waste processing has not degraded in service or has not been modified without approval,
- Assuring that all important parameters of the waste packages are kept within established limits,
- Assuring that the facility is being operated according to the assumptions of the safety analysis,
- Assuring that only containers qualified by performance based testing are used and that their use is only within their qualification limits.

13.5.3. Product auditing

Product auditing usually involves directly examining a waste form, a waste container or a waste package. It should be performed when the auditing organization possesses testing technology or expertise and the waste processor does not. Product auditing should also be performed when the waste processor samples, tests or examines its products on an ongoing or statistical basis. Normally, determination of compliance with a product’s requirements will be built into a QA programme as a quality control or verification activity performed by the producer. A system audit will confirm if the verification is being performed. Product audits may become the responsibility of the waste management organization when the waste producer lacks the infrastructure to perform quality control functions.

13.5.4. Waste producer audits

Waste producer audits are necessary to ensure that the organizations producing the waste comply with the waste acceptance criteria and properly document their waste packages. Periodic waste producer audits may be a contractual or regulatory requirement for the continued access of a waste producer to a waste management facility.

14. CONCLUSIONS AND RECOMMENDATIONS

This report intends to provide practical guidance primarily to developing Member States for the handling, processing and storing of radioactive waste arising from medical, industrial, research and other nuclear applications. Conclusions and recommendations derived from this report can be summarized as follows.

1. The applications and characteristics of radionuclides used in medicine, industry and research are extremely diverse. Sources and the waste itself must be fully characterized in radiological, chemical, biological and physical terms as a precursor to effective waste management.
2. Most radionuclides used in nuclear applications, and especially those used in medicine for diagnostic purposes, have relatively short half-lives (i.e. a few hours to a couple of months). Therefore full use of on-site decay methods should be utilized to allow disposal of waste as non-radioactive refuse after a suitable period of storage.
3. Minimization of waste arising and adequate management of waste should be the primary focus of any waste management programme.
4. A national radioactive waste management infrastructure and regulatory framework is an important part of any radioactive waste management system.
5. On-site processing of locally generated radioactive waste is preferable if practical, appropriate and cost effective. Centralized waste processing facilities serving a number of users can be cost effective when individual users do not produce sufficient quantities of waste to justify their own facilities.
6. The non-radiological hazards of waste, such as physical (e.g. sharps), infectious and chemical hazards, must be considered. Safety precautions such as those defined in standard infection control or chemical handling texts must be practised.
7. Waste operators should implement the process options for radioactive waste management that are the most cost effective to procure and operate, and which satisfy all local and national requirements. Process selection, especially in developing Member States, should be based on relatively simple, robust technology that is readily available and maintainable and is adequate to treat the expected waste arisings.
8. Where volume reduction of dry active waste is required, simple in-drum compaction is recommended as a cost effective solution.
9. Where the immobilization of waste is required, the use of Portland cement based materials should be considered owing to its widespread availability and its cost effectiveness.
10. Quality assurance, covering handling, packaging, training, auditing, risk assessment, the relevant regulatory requirements and record keeping, should be implemented for all steps and components of a waste management strategy.

11. When developing a waste management strategy, consideration should be given to the entire sequence of waste management operations from the waste’s production to its final disposal, and all related issues, including the various regulatory, sociopolitical and economic issues. The interaction of all these aspects must be analysed and understood before the entire waste management system can be properly built up and safely managed.
12. The management of radioactive waste is not a static process. Annual reviews of on-site and centralized programmes should be conducted, as:

- New uses and procedures may alter the characteristics of the radioactive waste;
- Changes of regulations in Member States may require revisions of management procedures and strategies;
- Changes in volumes and composition of the radioactive waste may result in new pricing structures, or the final disposal route may increase its pricing structure, making use of that disposal route no longer viable.

It is further intended that the information in this report is used to initiate new waste management programmes, or for modifying and/or extending ongoing ones.

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Consultants Meetings

Vienna, Austria: 18–22 November 1996, 1–5 September 1997,
8–12 December 1997, 14–18 December 1998