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Selection of efficient options for processing and storage of radioactive waste in countries with small amounts of waste generation

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SELECTION OF EFFICIENT OPTIONS FOR PROCESSING AND STORAGE OF RADIOACTIVE WASTE IN COUNTRIES WITH SMALL AMOUNTS OF WASTE GENERATION
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FOREWORD

Much information is currently available on waste management technologies and their alternative designs. Technologies can be selected on the basis of national organizational preferences and experience, or optimization procedures. Because of the cost involved, the potential complexity of technical and environmental considerations, as well as the necessity to ensure adequate performance, the selection process may be rather complicated, especially in countries with limited waste generation, limited experience and inadequate resources.

The present report is intended to assist decision makers in countries using nuclear energy for non-power applications to organize their waste management practices. It describes methodologies, criteria and options for the selection of appropriate technologies for processing and storing radioactive waste generated by these applications. The report reviews both technical and non-technical factors important for decision making and planning, and for implementation of waste management activities at the country and facility levels. It makes practical recommendations for the selection of particular technologies for different scales of waste generation.

The report was prepared by the Secretariat with the assistance of consultants from five countries through a series of consultants meetings, based on information collected and analysed from recently published technical reports and documents on specific waste management technologies. The IAEA would like to express its thanks to all those who took part in the preparation of the report and its revision. The IAEA officer responsible for the publication was V. Efremenkov of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Radioactive waste processing technology is a subject that has received considerable attention in the Member States in recognition of its importance for the protection of human health and the environment from adverse effects of radiation associated with radioactive waste. A large body of information is currently available on proven waste processing technologies and their technical alternative designs and on ‘emerging’ technologies, which require further development and/or validation. Most of the existing technologies have been developed for processing of large amounts of operational radioactive waste from such facilities as nuclear power plants and other nuclear fuel cycle facilities. Nuclear power was established several decades ago and most nuclear power plants and nuclear fuel cycle facilities were equipped from the very beginning with industrial scale facilities needed to process large volumes of radioactive waste with more or less typical characteristics. Waste processing facilities have been improved significantly since that time to meet stricter requirements for effluent discharges and waste disposal that have evolved with time.

However, in countries, which have no extended nuclear programmes but only limited nuclear applications with generation of a rather limited amount of radioactive waste, frequently there are no efficient and effective waste processing facilities. Wastes generated from various nuclear applications, such as research activities, use of radioisotopes for medical treatment and diagnosis, etc. in some cases are stored in untreated and unconditioned states. Modern safety requirements require waste generators to provide at least safe storage for radioactive waste that involves some processing technologies in order to bring the waste into a stable condition.

Selection and/or adaptation of adequate waste processing technologies for rather limited amounts of radioactive waste generated in these countries is not a simple process. There are two main reasons for this. One is *the cost of waste processing*. At commercial power plants the cost of waste processing can be incorporated into the cost of energy generated. That is not the case for waste from nuclear applications in general, although in the case of industrial irradiators this possibility could be considered. Another one is *diverse waste characteristics*. The waste arising from nuclear applications is characterized by low volume but basically they are highly diverse in nature.

Selection of waste processing technologies and facilities among those available on the market should be optimized and follow certain criteria. Some criteria will be rather general and apply to almost all waste management systems. The generic criteria and factors affecting the selection and implementation of particular waste management technologies are analysed in several publications (in particular [1]), however some guidance is still needed on how these generic criteria should be considered and applied to solve a particular waste management problem.

Many countries with a limited number of nuclear applications and limited waste generation cannot afford the most sophisticated technologies for treatment and conditioning of their radioactive waste. Rather simple, robust and reliable processing technologies must be applied to limited waste streams to achieve the required and sufficient level of safety and the appropriate level of efficiency.

1.2. OBJECTIVE

The objective of this report is to provide Member States, their responsible organizations and personnel with guidance on practical steps needed to select appropriate and efficient technologies for processing and storage of radioactive waste from different nuclear applications. The report addresses practical considerations for the selection of a particular waste management scheme based on the critical review of the related technical and non-technical factors affecting this selection, and taking into account radiological safety of workers, the public and protection of the environment.

1.3. SCOPE

Based on the analysis of fundamental requirements for management of radioactive waste and particular requirements of national waste management system, the report discusses the factors and the criteria which should be considered when selecting particular options and appropriate technologies for processing and storage of low and intermediate level radioactive waste from different nuclear applications. These wastes may arise from production of radionuclides and their application in industry, agriculture, medicine, education and research. The report also considers waste generated at research reactors, research centers and research laboratories using radioisotopes, as well as waste from decommissioning of research reactors and small nuclear facilities such as hot cells, laboratories and irradiation facilities.

Management of uranium mining and milling waste and management of spent fuel from research reactors are not considered in this report, since these subjects are specifically addressed in other publications. The waste generated from the technologically enhanced concentration of naturally occurring radioactive materials (NORM) is also excluded from the scope of this report, although some techniques and approaches discussed here may be considered and applied for processing of this type of waste.

1.4. STRUCTURE OF THE REPORT

Section 2 addresses the basic legal, regulatory, administrative and technical requirements set up in a national waste management system and reviews the factors and components affecting the selection of an appropriate national waste management system.

Section 3 briefly introduces the origins and characteristics of radioactive waste from different nuclear applications.

Section 4 addresses the technical factors that might affect the selection of waste processing and storage technologies.

Section 5 introduces the main waste management steps, provides information on available technologies and discusses the basis for planning of waste processing and storage.

Section 6 provides advice on the selection of a particular option for radioactive waste processing and storage in countries with a different scale of nuclear applications.

Section 7 provides short conclusions.

2. REQUIREMENTS OF THE NATIONAL WASTE MANAGEMENT SYSTEM

Selection of waste processing options and particular technologies in countries with limited waste generation is mainly defined by volumes and characteristics of waste and the identified national waste management regulations. The following requirements are considered to be included in the national radioactive waste management system and they are mandatory for the majority of Member States:

(a) Establishing an appropriate set of radiological and environmental protection objectives, associated legal framework to fulfill these objectives and an independent regulatory capability;
(b) Identification of the parties involved in waste management activities and their responsibilities;
(c) Identification of existing and anticipated radioactive wastes, including their location, average amount, radiological, physical and chemical characteristics;
(d) Identification of available and required capacities and facilities to process, store and dispose of radioactive waste on an appropriate time-scale;
(e) Identification of a funding structure and allocation of resources that are essential for radioactive waste management, including decommissioning and disposal.

All these requirements are interdependent and equally important. If some of these requirements are not met, the safety and effectiveness of waste management in the country may be compromised.

2.1. ORGANIZATIONAL STRUCTURE

Waste management practices of any country depend on the structure of the waste management organization. The complexity and size of the organizational waste management structure would depend on the quantity and diversity of the waste involved. In cases where the quantities of generated waste are low, responsibility and authority may rest with a few individuals. On the opposite end of the spectrum, the organizational structure may include multiple waste generators and a central waste management organization. In both cases it is vital that authority for decisions on waste management and responsibility for waste management implementation be clearly defined.

2.2. SAFETY REQUIREMENTS AND CONDITIONS

Management of radioactive waste, as a potentially hazardous activity, is normally controlled within a framework of national legislation. Relevant international requirements and recommendations also address the protection of human health and the environment from negative effects of ionizing radiation, including those associated with radioactive waste. National legislation may use the international requirements and recommendations as a basis for development of national laws, regulations, rules and norms dealing with radioactive waste management and related problems, such as radiological protection, discharges of radioactive effluents, storage, transport and disposal of radioactive waste. Compliance with all relevant international requirements and recommendations embodied in national legislation should be ensured during all phases of radioactive waste management.

Principles and requirements for establishment of a legal basis and a particular legislative structure of radioactive waste management are discussed in detail in several publications of the IAEA — safety fundamentals and requirements [2–5]. Depending on the scale of nuclear applications and corresponding waste management activities the legislative structure may consist of one or more special laws or amendments to the existing most appropriate and relevant law, e.g. on environmental protection, health care, etc.

2.2.1. International recommendations, standards and agreements

The International Commission on Radiological Protection (ICRP) has developed recommendations aimed at the protection of human health and the environment from the hazards associated with any source of ionizing radiation [6, 7]. These recommendations are based on a substantial body of scientific knowledge and a wealth of experience in dealing with radioactive materials. The IAEA, as one of its statutory functions, establishes or adopts standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes based on these recommendations [8].

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA for application in relation to its own operations and to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the design, construction, commissioning, operation and decommissioning of a nuclear facility or any other related activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, final decisions and legal responsibilities in any licensing procedure rests with the Member States.

The IAEA's safety standards programme for radioactive waste is aimed at establishing a coherent and comprehensive set of principles, objectives, requirements and recommendations for the safe management of radioactive waste and formulating the guidelines necessary for their application. This is accomplished in the IAEA Safety Standards Series, an internally consistent set of standards that reflect an international consensus. The publications provide Member States with a comprehensive series of internationally agreed safety standards to assist in the derivation of, and to complement, national criteria, standards and practices.

The basic principles of radioactive waste management are set out in the Safety Fundamentals publication on The Principles of Radioactive Waste Management [5] and are further elaborated for different stages of radioactive waste management (predisposal, disposal, decommissioning) in Safety Requirements [2–4]. Guidance on the implementation of the requirements is provided in a number of associated Safety Guides.

Some other publications issued by the IAEA, which are generally considered recommendations, although not obligatory to Member States, may be very useful for creating national legislation in the field of radioactive waste management. In this regard the IAEA Code of Practice on Transboundary Movement of Radioactive Materials [9] is of importance. Its provisions may exclude some States from managing radioactive waste of foreign origin if the recipient State does not comply with specific conditions.

International legal instruments have a significant influence on radioactive waste management in Member States. States that are parties to international conventions need to comply with their requirements, which may restrict or require certain waste management activities or options. In this respect, the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management imposes binding obligations on Member States party to it [10].

2.2.2. National legislation

2.2.2.1. Safety requirements

One of the basic waste management principles requires that the safety of facilities generating and/or managing radioactive waste be appropriately assured during their lifetime. The design, construction, operation and decommissioning of a waste generating or waste management facility should be carried out giving safety matters priority in order to achieve the design objectives, prevent accidents and limit negative consequences, should accidents occur. The design should be such as to provide, where appropriate, several levels of protection to limit any radiological consequences.

Consistent with national regulatory requirements, a safety assessment is an important tool to ensure the safety of operation and is needed for:

- new waste management facilities and practices, and
- significant modifications of existing facilities or practices.

Such assessments are used to demonstrate compliance with national regulatory requirements and to provide a basis for the regulatory body to review and approve the particular practices and operation of the facilities concerned. The level of details of such assessments should be commensurate with the risk posed by the practice or the facility.

2.2.2.2. Radiological protection requirements

Selection of waste processing technologies is strongly influenced by the radiological protection requirements for workers, the public and the environment. The system of radiation protection makes a distinction between a ‘practice’ and an ‘intervention’ [8]. For a practice the radiological protection requirements are based on *justification* of practices that lead to potential exposure.

No special justification is needed for waste management activities, since the activities which generate radioactive waste must themselves be justified. However, optimization of the waste management option chosen should be considered thoroughly as well as dose limitation:

(a) all exposure should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account, and
(b) the dose equivalent to individuals should not exceed the limits identified for the appropriate circumstances.

For the ‘intervention’ situation, which is relevant, for instance, in the case of the management of old, not adequately treated and conditioned waste, *justification* and *optimization* are both applicable, but in certain situations not dose limitation. Justification of the intervention needs to consider the additional dose (harm) resulting from the activities during the intervention as well as the reduction of the dose, which is the result of the intervention. The intervention will give occupational exposure to the workers involved in the work, but the future dose, both for operators and the general public, will be reduced owing to, for example, a properly conditioned and disposed of historical waste. Those issues are further developed in Ref. [8].

2.2.2.3. Environmental protection requirements

Protection of the environment is an important consideration, when managing radioactive waste and establishing waste management facilities. Most national legislation requires an environmental impact assessment to be made for new waste management facilities and practices, and for significant modifications of existing facilities or practices. Such assessments should be made to analyze and demonstrate that the protection of the environment is ensured during normal operations and to assess the potential effects of incidents and accidents. The assessments should demonstrate compliance with national regulatory requirements and provide a basis for the regulatory body to review and approve the particular practices and corresponding facilities. They should take account of the complexity of the respective practice or the facility.

The environmental impact assessment should be carried out before irrevocable decisions are made regarding a waste management project, and should cover all phases of the project: site selection, site preparation, construction, operation, and decommissioning. The assessment should identify any mitigatory measures necessary to protect human health and the environment. These measures, which ensure that there are no significant adverse effects on the environment, are an integral part of waste management. The technology chosen should ensure that mitigatory measures are practical and effective.

2.2.2.4. Operational safety culture

The success of waste management programme implementation within the organization will depend in large degree not only on the appropriateness of the waste management technology being employed, but also on the standard/level of operational safety culture maintained.

Upper management is responsible for maintaining high operational safety culture at the facility regarding the safety of workers under their authority and the safety of the general public. An operational safety culture should be fostered and maintained to encourage a questioning and learning attitude to protection and safety and to discourage complacency, to ensure that:

- Policies and procedures are established that identify protection and safety of the public and workers as being of the highest priority;
- Problems affecting protection and safety are promptly identified and remedied in a manner commensurate with their importance;
- The responsibilities of each individual for safety are clearly identified and each individual is suitably trained and qualified; and
- Personnel have both the capability and the motivation to achieve safety objectives.

An important principle of radioactive waste management is waste minimization, which at the same time is an important element of general operational culture. Savings in both occupational exposures and waste management cost can be achieved by screening the waste generating practice and modifying it in view of waste minimization. Appropriate on-site segregation of the waste, considering subsequent treatment, can contribute significantly to waste minimization, reduction of doses and the cost of the subsequent waste processing operations.

2.2.2.5. Non-radiological requirements

The technology employed in a waste management system needs to provide for the protection of human health and the environment, not only from ionizing radiation, but also from potentially hazardous chemicals. These issues are especially important when managing mixed waste, i.e. waste comprising both radioactive materials and chemical or biological toxic materials. The protection of human health and the environment is achieved by imposing certain restrictions on these non-radiological effects. These restrictions are aimed at the protection of air quality, surface water and groundwater, the environment in general, and natural resources, in particular. These restrictions are given in relevant national laws and regulations and may affect the choice of waste management technologies and practices.

2.2.2.6. Waste regulatory control requirements

Radioactive waste arising within a practice that is under regulatory control may be released from control under conditions specified by the regulatory body [11–13]. If it can be shown that any radiological hazards resulting from the release are negligible the materials can be released from regulatory control. Release can apply both to materials that are being discarded as waste and to materials intended for further use or recycling. Consequently, released materials may be treated as normal refuse or effluent, and materials released for re-use or recycling may be sold to any other party and used for any purpose.

Release from regulatory control is an efficient mechanism for reduction of the volume of radioactive waste. Release levels may be established in the national legislation or on a case-by-case basis.

Derived release levels are calculated on the basis that the dose criteria for release are met for all relevant scenarios of exposure from the material [12]. Release levels may be stipulated as activity limits and/or activity concentration limits.

In making a case-by-case permission for release, the regulatory body should assess the type and quantity of materials to be released, the characteristics of the radionuclides, the end use and the means of achieving it and the potential pathways to man for the probable scenarios. For many cases a simple safety assessment of the risk to man, based on pessimistic assumptions, is sufficient to satisfy the authorities that the risk is negligible. On the basis of this assessment the regulatory body sets the maximum total activity or activity concentrations levels. Sometimes, due to the difficulty in carrying out such a safety assessment, developing Member States use the exemption limits defined in Ref. [8] as release levels, which represents a sufficiently conservative approach for small quantities of material. The case-by-case approach has some implications: as a full safety assessment has not been done in the majority of such cases and the internationally proven limits are not used, the authorities may request more strict monitoring.

Control of discharges of radioactive effluents is normally exercised through the granting of permits, licenses, or other authorizations by the regulatory body to the operator of a facility. Such licenses, etc. usually stipulate routes and conditions for discharge of various waste effluents, and the limits, in terms of specific and/or total activity, as conditions with which the operator must comply. In granting an authorization the regulatory body considers the capability of the operator to comply with its conditions, which might include record keeping and arrangements for environmental monitoring [13].

When it is unacceptable that regulatory control be relinquished, radioactive materials must be dealt with by *disposal* in a licensed repository, in the case of waste, or *transfer* to another license holder. Consideration should also be given to non-radiological hazardous content of the waste stream such as heavy metals or other toxic constituents. These non-radiological factors could also have an impact on the safety of waste disposal.

2.2.2.7. Transport regulations

If radioactive waste is to be transported outside a waste processing/storage facility, it must be done in accordance with the national transport regulations. The national transport regulations are commonly based on IAEA Safety Standards Series No. TS-R-1 [14]. The IAEA regulations specify the requirements for packaging and labeling, and define transport categories of radioactive materials according to their radioactivity content and radiation level.

As many small waste generators have no capabilities to package radioactive waste in full compliance with the IAEA requirements, for small amounts, low specific activity (LSA) or surface contaminated objects (SCO) special arrangements are commonly used. In this case much effort needs to be made by the regulatory body and transport organization to ensure transportation safety. Such special arrangements may place a large burden on the parties involved. There is also a need to maintain a well-established emergency management system for the managing of any waste resulting from incidents or accidents.

It should be noted that it is impossible to introduce properly designed, tested and licensed containers for the transport of radioactive waste without significant investments of time and money. It is an issue where international co-operation is vital to increase the safety and to reduce the cost of radioactive waste management.

2.3. COST AND FUNDING

The cost of different waste management technologies can vary greatly. A basic non-technical requirement of the national waste management system, which may greatly affect the selection of a technology, lies in the financial resources of the waste generator or the state and their willingness to commit them to establishing an efficient technological system. The lack of adequate funding could compromise the efficiency and safety of waste management system as a whole.

In planning of a waste management facility, the following parts of the ‘total life cycle cost’ should be considered:

- All costs for investment, depreciation, operation, decommissioning, and manpower;
- Costs associated with handling of secondary waste, for surveillance and monitoring; and
- Costs for research and development, demonstration, validation and/or adaptation.

All intermediate steps of waste management and final waste disposal are costly activities; however, at the time of first decisions, reliable cost figures may not be available. Volume reduction reduces the volume of material to be disposed of and affects cost of disposal. To the extent possible, all cost components have to be taken into consideration and there may be room and incentive for optimization, primarily for activities that generate large amounts of radioactive waste.

The proper funding of waste management activities must be ensured. The structure and mechanism of funding may vary from one State to another. The government that promotes nuclear applications normally supports related waste management operations and their regulatory control. However, the waste generator, to a certain extent, may be charged a certain portion of the waste processing cost by the central waste management operator, if there is one.

2.4. TECHNICAL CAPABILITY OF PERSONNEL

The availability of manpower with an adequate level of competence for operation, maintenance and repair of radioactive waste management equipment is an important factor. The appropriate technical capability of the staff to perform the assigned task must be established and maintained at every site where radioactive waste arises and/or is processed. This capability should be commensurate with the available facility to ensure effective and safe operation.

Processing of radioactive waste has to be done both at the local level, where the waste is generated, and at the central level, where the long lived radioactive waste is processed and stored awaiting final disposal.

The waste generator may not need to be aware of all details of how the waste will subsequently be managed, if the job of waste processing is left to the operators of waste management facilities. However, there is a need for the waste generator to be informed about the subsequent steps of waste management in order to appreciate the need to appropriately segregate the waste. If a centralized waste processing and storage facility does not exist, waste generators should have basic knowledge, training and appropriate capacities to process and store wastes after they are generated. The waste generator also needs the verification capability to ensure that radioactive waste to be released from regulatory control meets the national clearance levels. Although the safety assessment capability may not be available at the waste generator site, an overall safety assessment of the system, including the decay storage facility, should be done, possibly with the help of the central waste operating organization and the regulatory body. Where there is little national experience in performing a safety assessment, international assistance, e.g. through IAEA advisory services, can be helpful.

When a central waste operating organization exists, the largest technical capability of the staff needs to be established there. Its personnel should have basic knowledge and experience in management of radioactive waste, and should have equipment appropriate to its tasks in management of waste generated in the country. These personnel should have the competence to assess the safety and performance of the waste facilities and implement the quality assurance programme especially related to production of waste packages acceptable for storage, transport and disposal.

Because of the complexities of generation and distribution of radioactive materials in nuclear research reactors, it is essential that some of those responsible for waste management have the detailed understanding of the waste generation processes. This process knowledge will be necessary to estimate the concentration and hazard of radionuclides that could be difficult to measure and that could have long term impact.

The regulatory body must maintain its independence from the operator of a waste management facility, however the regulators should possess necessary technical knowledge and experience to administer laws and regulations and provide clear guidance and direction to the operators of waste management facilities.

2.5. PUBLIC INVOLVEMENT AND POLITICAL ACCEPTANCE

The introduction of a waste management facility within a country generally requires public participation in order to gain public acceptance. Failure to inform and involve the public and political decision-makers can result in rejecting an area designated for the development of a waste management facility.

An effective public information programme will be a useful effort in addressing concerns among members of the public. As far as it is appropriate the public should be brought into the process of site and technology selection. When they are part of the process, it is easier to get public acceptance. A lack of attention to this area can result in a negative impact on public perception, especially when organized opposition to the construction of nuclear facilities has already developed.

An additional obligation for informing the public about waste management issues is the 1998 Aarhus convention [15] which requires the parties concerned to ensure the availability and accessibility of information and provides the general public with the right to be involved in a decision making process. Compliance with the requirements of this convention may reduce the negative perception of planned waste management facilities and installations.

The public should be informed at appropriate stages of facility development and societal issues should be addressed throughout these steps.

2.6. OTHER NON-TECHNICAL FACTORS

2.6.1. Geographic conditions

The geography of the country can influence the suitability and the location of waste management facilities. For example, the location of a central facility may be affected by the distance to the main waste generators (in order to optimize transport of radioactive waste) and a large territory may affect the decision on establishing one or more centralized facility(ies) because the cost and problems of transport would be too great. High population density and the extensive use of land resources for agriculture may have an impact on the site selection for a centralized facility. In such a case, the waste processing facility may be designed to accommodate the particular constraints.

2.6.2. Opportunity for international co-operation

The availability of waste processing techniques and capacities in other countries (especially in neighbouring countries) should be considered when selecting a waste management technology. It may be possible to send the waste to another country e.g. for treatment and immobilization or to hire equipment from neighboring countries to facilitate, for example, volume reduction. In this connection, the existence of bilateral or regional co-operation agreements and projects can be very important to save money and reduce potential hazards to the population. Regional waste processing centers, storage facilities, and even disposal sites can provide a significant step forward in bringing the benefits offered by radiation technology to the people of many countries of the region.

Other forms of international co-operation to achieve the waste management goal include exchange of staff and agreements to accept certain types of waste e.g., spent fuel from research reactors or disused sealed radioactive sources. These agreements may be made by one country on behalf of another for a number of reasons, including, but not limited to, non-proliferation agreements, technology transfer or international co-operation.

The IAEA provides considerable assistance to developing Member States in the field of radioactive waste management by supplying some typical tools and equipment within its programme of technical co-operation. The programme also makes it possible to train local waste management personnel through different mechanisms and to provide qualified expertise on waste management technological issues by recognized experts.

2.6.3. Physical infrastructure

The extent to which waste management technology options can be adopted greatly depends upon the availability of basic physical services of Member States including transport, communication and on-site services. Accessibility to a site, availability of a transport system and local factories which may produce components (e.g. waste containers) needed for the waste management facilities are some examples of infrastructure components which can affect the process of selecting waste management site or technologies.

3. ORIGIN AND TYPES OF RADIOACTIVE WASTE

3.1. TYPICAL WASTE ARISINGS

Since practices in different Member States vary widely, to facilitate understanding of issues, progress, and problems within more than 130 Member States, the IAEA has grouped countries’ nuclear programmes into five classes. The grouping is done in accordance with the extent of the use of radioactive materials. The Member State classification may change when their nuclear programmes move from one group to another according to the criteria described in Table I.

Class A countries include Member States in which practices are represented by application of a few sealed radioactive sources and limited quantities of predominantly short lived radionuclides in medicine. These radionuclides are typically imported into the country.

TABLE I. CLASSIFICATION OF COUNTRIES BY SOURCE OF RADIOACTIVE WASTE

Class	Typical use of radioactive materials in Member States
A	**S**ingle **I**sotope **A**pplication – SIA (typically in a hospital)
B	**M**ultiple **I**sotope **A**pplications – MIA
C	**R**esearch **R**eactors and production of radionuclides coupled with their use in multiple **A**pplications – RRA
D	**N**uclear **P**ower **P**lants, research reactors and multiple isotope applications – NPP
E	**N**uclear **F**uel **C**ycle facilities, power plants, research reactors and multiple isotope applications – NFC

Class B countries use radioactive materials in a greater variety of applications, including the wide use of sealed and unsealed sources for medical, industrial, agricultural, research and education purposes. The radionuclides used may include both short lived and long lived ones. The waste generated comprises disused radioactive sources (including radium sources formerly used for brachytherapy) and larger quantities of various medical and biological waste with significant concentrations of short lived, but also some long lived radionuclides. The radioactive materials are typically imported into the country.

Class C countries practice all the activities of class B countries, and in addition, have nuclear research reactors in operation for basic research and/or radionuclide production. These activities are frequently carried out in one or two research centers with research reactors, supporting services, research and isotope production laboratories. In addition to waste typical for class A and B countries, the waste generated in class C countries will include ion exchange resins, liquid aqueous and organic waste, and various solid wastes, including waste items contaminated with fission or neutron activated products. Spent nuclear fuel is also generated at research reactors. The radioactive materials are typically imported into the country, but some of them could be produced at research reactors or by particle accelerators.

Besides solid and liquid waste some gaseous wastes are generated during operation of nuclear facilities, e.g. research reactor. These wastes may also arise from operations with gaseous or volatile radionuclides, as secondary waste during waste treatment, and as a result of failure of some fuel assemblies in the research reactors.

Class D and E countries are out the scope of this report with regard to radioactive waste generated from and at nuclear power plants and facilities of the nuclear fuel cycle. However, all these countries have different scale of nuclear applications, therefore approaches and options for processing of waste described in this report may well be applicable for management of respective waste in these countries.

Categories of radioactive waste arising in class A, B and C countries are illustrated in Fig. 1 and further briefly described in the following sub-sections. Estimation of typical amounts and activities of solid and liquid waste arising from different nuclear applications in countries with different scale of these applications are summarized in Table II.

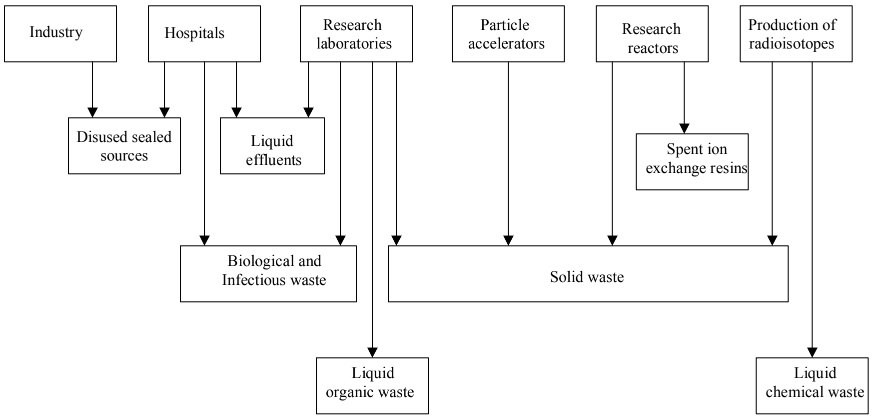

FIG. 1. Principal categories of radioactive waste arising from nuclear applications.

TABLE II. TYPICAL NUCLEAR APPLICATION WASTE ARISINGS

Waste type	**A countries**		**B countries**		**C countries**	
	m^3/a	GBq/a	m^3/a	GBq/a	M^3/a	GBq/a
Aqueous waste	$< 10^{-2}$	$< 10^{-1}$	10–50	<100	2–200	$< 10^4$
Organic liquids	$< 10^{-2}$	$< 3x10^{-2}$	0.1	< 0.1	0.1–1	$< 10^3$
Solid compactable	<1	$< 10^{-1}$	1–3	< 50	50–100	$< 10^5$
Solid non-compactable	–	–	< 1	< 0.01	1–3	$< 10^3$
Spent ion exchange resins	–	–	–	–	0.5–1	$< 10^3$
Biological materials	–	–	<0.1	<5	0.1–0.5	< 10
Disused sealed sources (pieces/a)	5–10	10^2	10–50	10^3	50–500	10^6

3.2. RESEARCH REACTORS

The size and thermal power of nuclear reactors used for research purposes varies from small critical or sub-critical assemblies to powerful reactors designed for production of radioisotopes and for testing of construction materials. The amount and characteristics of reactor operational waste depends significantly on the reactor power, but the radionuclide inventory and waste composition are generally uniform for a particular facility. The total activity of waste may be high. The main radionuclides in the waste are fission and activation products. Contamination with long lived alpha radionuclides may appear in the case of fuel element leakage. Radioactive waste falls mainly into the following categories:

- aqueous effluents (decontamination solutions, laboratory drains, washing water);
- organic effluents (oils, solvents);
- ion exchange resins (from cleaning of the reactor coolant and of water from the fuel storage pond);

- compactable solid waste (paper, plastics, gloves, protective clothing, filters);
- non-compactable solid waste (large activated metallic items).

3.3. PARTICLE ACCELERATORS

The use of particle accelerators may lead to the activation of some construction materials or parts by high energy particles. Radioactive waste may be generated during the removal or replacement of activated parts of the accelerator.

Another waste stream is related to the use of accelerators and neutron generators for scientific investigations, which are mainly based on neutron activation analysis. In these cases only relatively small amounts of radioactive waste are generated. Usually short lived isotopes are produced and decay storage for the waste is the preferable option. In a few cases treatment and conditioning for radioactive waste may be needed. Some accelerator based neutron generators use large tritium targets, which are the origin of tritium contaminated waste.

3.4. PRODUCTION OF RADIOISOTOPES AND RADIOPHARMACEUTICALS

Radioisotope and radiopharmaceutical production is usually carried out in irradiation facilities such as research reactors and accelerators. The waste from these activities reflects the applied technological processes both from chemical and radiochemical points of view and it is mostly uniform for a facility. Wastes are typically small in volume but may be highly radioactive and they may contain various radionuclides, including fission products, uranium isotopes and a number of very short lived nuclides. Wastes appear in the form of organic and aqueous effluents, ion exchange resins, compactable and non-compactable solid waste.

3.5. MEDICAL TREATMENT, DIAGNOSIS AND RESEARCH

Radioactive waste from application of radionuclides in medicine varies in radionuclide composition, content and volume. While low level waste is generated in large volumes, highly active waste arises in small amounts. Medical radioactive waste may be biotoxic or infectious and composed of organic materials (excreta, blood, carcasses, etc.). In radiotherapy high activity sealed sources are extensively used. High activity sealed sources can be used also for sterilization of surgical tools. Medical wastes can be grouped into the following categories:

- aqueous effluents (decontamination, washing and spent radioisotope solutions);
- organic liquids (scintillation cocktails, residues from organic synthesis, unused radiopharmaceuticals);
- compactable solid waste (laboratory dry and wet wastes);
- gaseous waste (from lung ventilation diagnosis);
- disused sealed radioactive sources;
- spent radionuclide generators;
- carcasses and biological materials.

3.6. APPLICATION OF RADIOISOTOPES IN INDUSTRY AND AGRICULTURE

Industrial and agricultural applications mostly use sealed radioactive sources, both for irradiation and for detection and measurements (gauges and smoke detectors). While other disused sealed sources can be of a high radiological risk, smoke detectors give rise to very low level waste and often they are considered as consumer products. Various short lived and long lived radionuclides are applied in different industries. Special attention should be paid to neutron sources, such as $^{238-239}$Pu-Be, ^{226}Ra-Be, ^{241}Am-Be, and ^{252}Cf.

3.7. NUCLEAR AND GENERAL RESEARCH

Research activities include a broad variety of methods and facilities, resulting in generation of different categories of radioactive waste, which depend strongly on the problems studied. The radionuclide inventory is also rather variable as research involves different radioisotopes with a variety of activity and concentrations. The waste types may include all kinds of aqueous, organic, biological and solid waste, depending on the particular research programme.

3.8. DECOMMISSIONING OF NUCLEAR INSTALLATIONS AND LABORATORIES

Decommissioning, especially of nuclear facilities, will generate significant quantities of solid waste during a relatively short period. During decommissioning of nuclear facilities using unsealed radioactive sources, the problem of waste generation is linked with the surface contamination of the equipment and building and with methods used for dismantling. Radioactive inventory will be mostly of low levels, and contamination will depend on the spectrum of isotopes used in the facility. The predominant waste arises from decontamination and demolition operations.

During decommissioning of high energy particle accelerators, waste containing activation products is generated. When dismantling a linear accelerator the problem is limited to the collimation heads, which may by contaminated by ^{57}Co, ^{60}Co and ^{181}W. Depleted uranium, which also needs to be treated as radioactive waste, has been extensively used for shielding. Biological shielding made of reinforced concrete may be contaminated with ^{60}Co, tritium, ^{152}Eu and ^{154}Eu.

Decommissioning of research reactors involves similar problems and, furthermore, the reactor vessel and system components may be activated to high levels requiring remote dismantling. Inside the reactor, internal surfaces will be contaminated by corrosion products and may also be contaminated by fission products and long lived alpha emitting nuclides if there has been fuel leakage. Beryllium, frequently used to increase the neutron flux in research reactors, poses a special waste problem due to its high chemical toxicity combined with its induced activity.

4. TECHNICAL FACTORS AFFECTING THE SELECTION OF WASTE MANAGEMENT TECHNOLOGIES

There are many technical factors that influence the choice of a waste management technology. The relative importance of the factors will depend on the particular application and problem the technology addresses.

4.1. WASTE CHARACTERISTICS

The characteristics of radioactive waste have a major technical influence on the selection of waste management technologies. Indeed failure to obtain and understand the characteristics of the waste before selecting the technologies will increase the risk of the process not operating satisfactorily. Wastes should be characterized according to their physical, chemical and biological properties since depending on these properties a particular waste processing technology can be selected.

The *physical properties* of the waste place basic constraints on the range of acceptable waste management technologies. Physical properties of the waste that may affect the selection of a waste treatment technology include:

- physical state (solid, liquid or gas), volume, mass and dimensions of waste items;
- type of radionuclide (activity, activity concentration, half-life, type of emission, decay chain);
- density (as received and theoretical density);
- morphology (powder, sludge, crystalline, colloids, aerosols);
- compactability;
- level of segregation (i.e. one discrete waste type or a mixture).

Consideration of the following *chemical properties* will aid the identification of appropriate technologies for treatment and immobilization of liquid waste:

- chemical composition (including chelating agents);
- organic content;
- acidity/alkalinity (pH);
- chemical stability;
- toxicity;
- redox potential.

Biological properties will play a part in the technology selection for waste treatment. The presence of any infectious or bio-toxic hazards may require specific processing steps.

Much of the waste held by Member States is 'historical waste' generated some years ago, which may have been inadequately or inappropriately processed and stored. In these cases the waste condition (degree of degradation of the waste or its packaging) has influence on the choice of technologies, if these waste require recovery and reconditioning.

The gaseous waste characteristics should be known because they are used as source terms for the design of ventilation and off-gas cleaning systems. Airborne radioactivity occurs in either particulate or gaseous forms, which may be present in a variety of chemical combinations. However, dispersal of radioactive substances into the air depends on many factors, such as their physical and chemical properties, work procedures and environmental conditions during handling and processing. In some facilities, the full range of radionuclides and work procedures will not be known at the design stage. Therefore, in many cases it is not possible to prepare adequate source terms for this purpose, and the ventilation and process off-gas cleaning systems design will have to be based on estimated levels of airborne radionuclides from anticipated operations.

4.2. SCALE OF TECHNOLOGY APPLICATION

The quantity of waste and its rate of generation will have a considerable influence on the scale and design of the waste processing and storage facility. If waste quantities are large and there are constraints on the size of a waste management facility, volume reduction could be justified. In general, large quantities of waste will require potentially more dedicated and expensive facilities and equipment. Equipment can be installed in situ, or in some cases hired (e.g. a mobile waste compactor or supercompactor). Small volumes of waste, on the other hand, will require simpler, less expensive and more generic equipment and facilities.

Some processes may be restricted to small scale applications e.g. those which require manual handling (e.g. preparation of disused radioactive sources for storage/disposal) or new processes for which extrapolation to a large scale application may need more development and evaluation. Some equipment may have a limited throughput. Other processes are characteristically large scale ones such as compaction/supercompaction of solid waste.

Embodied in the scale of application is a choice between a central processing and storage facility to which waste is transported, a facility or facilities co-located with the waste production sites or a movable waste processing unit. This choice will be dictated in turn by non-technical factors such as cost, transport regulations, etc.

4.3. MATURITY OF TECHNOLOGY

There are numerous technological options for management of radioactive waste, however it is necessary to collect reliable information about the maturity of the process. The term ‘maturity’ covers a complex set of parameters such as:

- The level of demonstration or application (past and present);
- The type of waste processed (surrogates or real waste);
- The licensing status;
- The availability of suppliers and services;
- The practical operating experience (cost, throughput, reliability, compliance, maintainability);
- Information on the current uses of the technology (for verification of the supplier’s claim and identification of any problems experienced in use).

For all applications there are advantages in reducing cost and risk by using mature technologies and avoiding extensive development and modification programmes. It should be noted that for the countries concerned all basic required waste management technologies are available.

4.4. ROBUSTNESS OF TECHNOLOGY

The term ‘robustness’ of a technology is not strictly defined; it refers in general to reliability in varying conditions of operation and maintenance, but in particular to:

- Sensitivity of the technology to composition and variation in nature of the input waste;
- Sensitivity to operating parameters;
- Dependence of the process upon up-front detailed characterization of input materials;
- Complexity of start-up, maintenance, shutdown and decommissioning operations.

Deficient robustness may have to be compensated by careful pretreatment, e.g. segregation, homogenization and characterization of raw waste, by local availability of other treatment technologies or more qualified operators. Since the pretreatment intervention is costly and may lead to additional personal exposure, robustness is an important criterion in the technology selection process.

The penalty for choosing a process that is not robust is that it will require detailed characterization of the waste before treatment, may not accommodate changes in the waste characteristics and may need high qualification and training of personnel.

4.5. FLEXIBILITY OF TECHNOLOGY

Whilst robustness covers the sensitivity of a process or technology to the waste stream, flexibility covers the number of waste streams the technology can accommodate. It represents the difference between a well tuned technology that is very effective for one waste stream and another that is applicable for many waste types. For example biological processes may be able to degrade and destroy specific toxic organic materials and can operate at a low capital cost whilst an incinerator can destroy virtually all organic materials but carries a relatively high capital cost. Another example is waste encapsulation with ordinary cement or modified cement. The later can accept a wide range of liquids, sludge, solids, organics and produce an acceptable product.

This criterion addresses a balance between a small simple specific technology, to which the generator of a single waste stream might resort, and a larger, more versatile technology that might be used at a central processing facility.

4.6. SITE CHARACTERISTICS

Site characteristics have implications for both waste processing and storage facilities. The characteristics include hydrogeology, seismicity, climate, the proximity of airports, populated areas, water, power, personnel, etc. The types of technical decisions made against these characteristics might, for example, be a greater reliance on discharges of gaseous or liquid effluents into the environment. The necessity to manage 'historical' waste may mean that the scale and permanence of the waste management facility (and equipment) may vary over the lifetime of the facility.

5. WASTE PROCESSING AND STORAGE PLANNING

5.1. WASTE MANAGEMENT STRATEGY OPTIONS

Elaboration of a suitable strategy and choice of appropriate technical options are key points for the successful development of a waste management programme. A strategy for management of radioactive waste would be based on a national policy. Ideally, the strategy should be determined before the system is put in place. In practice, one strategy, or a mixture of strategies exists. Examples of waste management strategy components include on-site management of the waste, management at a centralized facility, and a mixture of these two options.

On-site pre-disposal management of waste at the point of its generation involves the handling, treatment, conditioning, and storage without movement of the waste from the site of its generation, and may also involve on-site discharges of effluents and release of cleared waste. This waste management strategy eliminates the hazards associated with transportation of unconditioned waste to a centralized facility. However if more then one site exists it may involve the development and maintenance of redundant capabilities for waste management for each facility operating under this scheme.

Also, if there is no licensed repository, on-site storage is mandatory and due attention should be paid to the accumulation of waste at one storage site with the potential for safety problems. This strategy may be implemented in class A countries for economic reasons as long as the primary safety considerations are not compromised.

Centralized waste management includes many of the waste management steps and the transfer of waste to one location accessible by all waste generators. For this purpose, a transportation system must be instituted for transferring the waste from the generation sites to the central facility. Waste generators are required to prepare the waste according to specifications developed for transport of radioactive material and criteria for acceptance of waste by the central facility. This facility, depending on the strategy, may take over the responsibility for the waste from the waste generators, including processing and storage. When a disposal facility becomes available, the stored waste will be transferred for disposal.

Some short lived waste may never require disposal at a central location. This waste is typically comprised of short lived radionuclides which can be safely held for decay and be disposed of as non-radioactive waste (obviously, consideration should be given to decay products). It is generally not beneficial to transport short lived waste to a central waste processing and storage facility.

To minimize the amount of waste transferred to a centralized facility, a mixed system of on-site storage for decay and packaging for transport based on the total activity and half-life, could be introduced (see Fig. 2). International services for waste treatment and packaging may also be considered, if the capability within its own borders does not allow the country to manage existing or projected waste streams adequately.

5.2. INTERRELATIONSHIP OF WASTE MANAGEMENT STEPS

Waste management includes all administrative and operational activities covering handling, pretreatment, treatment, conditioning, transport, storage and disposal of radioactive waste (Fig. 3).

To achieve the overall goal of safe waste management, component steps must be complementary and compatible with each other. In this respect it is particularly important that no step should preclude or compromise subsequent waste management steps. The waste management system consists of the set of technologies that are applied to a waste from its generation to its disposal.

Normally, it is the responsibility of the operator of a waste generating facility to develop a waste management plan commensurate with existing or contemplated waste arisings that will serve as a guideline governing the waste from its origin, through processing and storage, to its

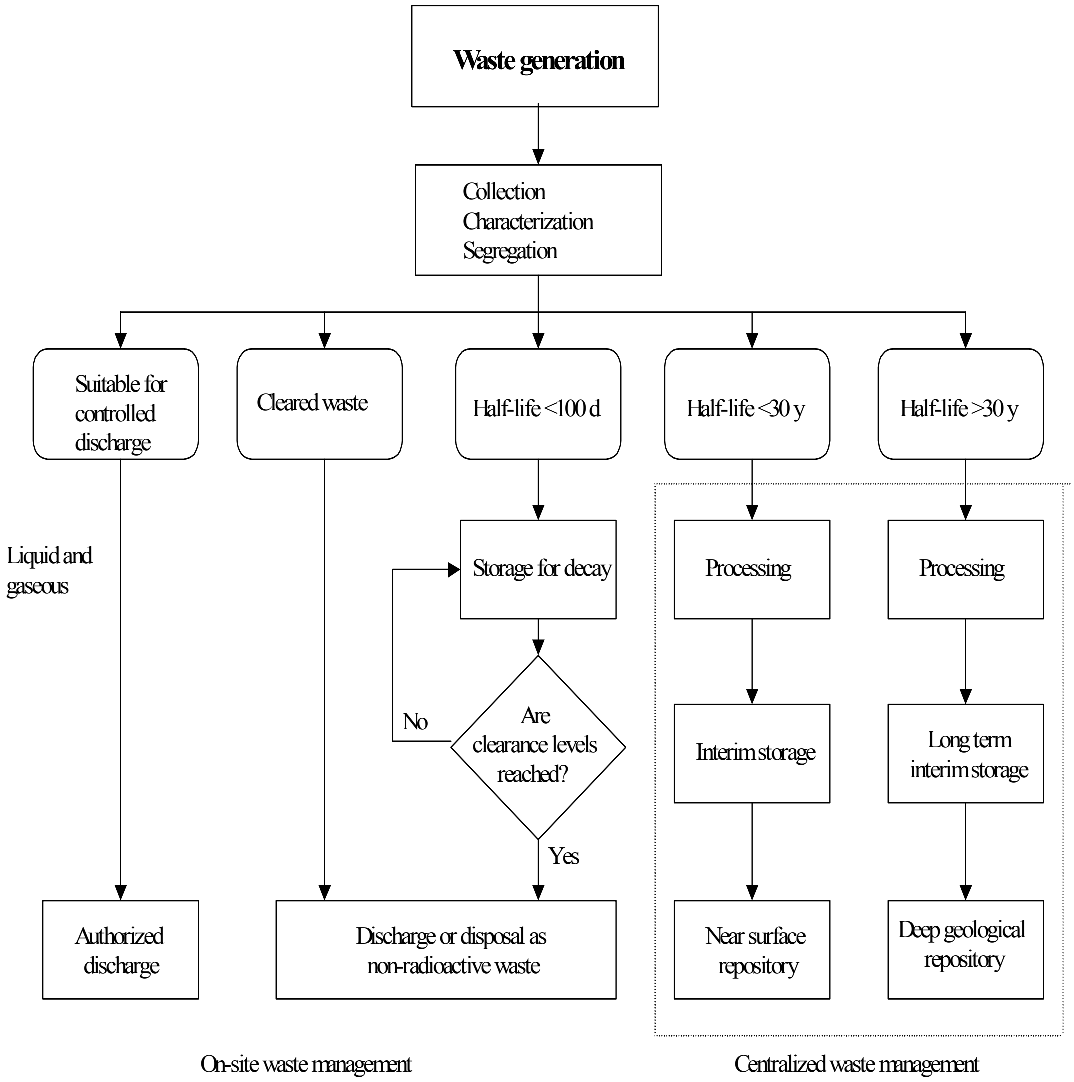

FIG. 2. Local and central waste management.

final destination. The operator has to use this plan as support for any application to the regulatory body for the authorization of its activities, dealing with radioactive waste generation, or with management of this waste itself. If a centralized organization or facility is available for management of radioactive waste, the waste management plan should be developed in co-operation with this organization taking into account its specific capacities and requirements.

In establishing the waste management plan, all stages in waste processing should be considered, starting from waste generation, through sorting and treatment until storage of conditioned waste or its ultimate disposal, if a disposal route is available. Technical options for treatment and conditioning of waste may vary depending on volumes and characteristics of waste generation, availability of resources, particular regulatory requirements and other country-specific and site-specific factors. However, the technological options identified for waste processing should be appropriate and sufficient to reach the basic objectives of waste management – to ensure safety for operators, general public and the environment.

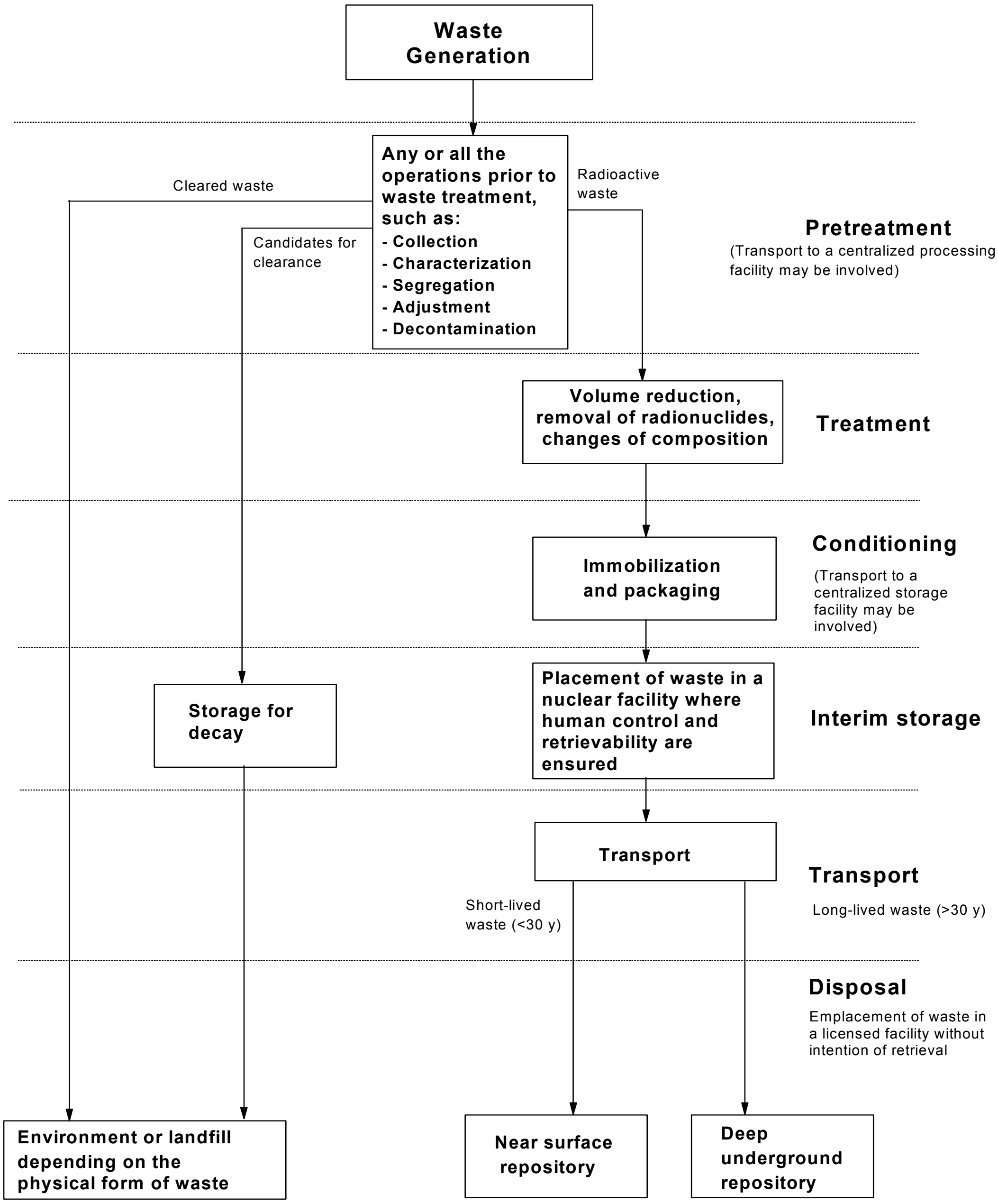

FIG. 3. Waste management steps.

At the early stages of planning, it might not be possible to define the disposal route for all waste streams. It might be decided that because the actual disposal route is unclear for certain waste streams, waste management steps should focus on stabilizing the waste for long term storage, in a form that can be adapted at a later time to meet the waste acceptance criteria for disposal.

The selection of a technical option for a particular waste processing step should fit into an overall plan for the management of all wastes under consideration, to form a system suitable for processing all waste types in the most efficient way. The technological options available for various liquid, solid and gaseous waste are described in the following sections.

5.3. REVIEW OF AVAILABLE TECHNOLOGICAL OPTIONS

Before selecting a particular technology or set of compatible technologies it is necessary to know the available technological options, which meet the above mentioned requirements.

5.3.1. Pretreatment

Pretreatment involves a variety of activities applicable to liquid and solid radioactive waste and can be defined as any operations preceding waste treatment [16]. The main objectives of pretreatment are to:

- segregate waste into active and non-active streams in order to reduce the volume of radioactive waste to be processed;
- separate an active stream into components or to convert the waste into a form so that it may be easily treated, conditioned, and packaged for storage and/or disposal.

The benefit of pretreatment is improved safety, lower radiation exposure and significantly lower costs in subsequent waste management operations. These benefits must be balanced with radiation exposure and costs for pretreatment. Since pretreatment is generally the first step in waste management and since every step in a waste management strategy limits or directs all succeeding steps, increased attention to pretreatment should create a positive impact throughout the rest of the waste management cycle.

5.3.1.1. Up-front waste characterization

The success of treatment and conditioning depends largely upon the knowledge of the nature and composition of the waste to be processed. Therefore, it is essential that sufficient information is at hand concerning its properties. To some extent, classification [17] and characterization [18] of waste allows application of specific processes and less detailed characterization may require more robust processing technology, less sensitive to the occurrence of some non-specified components.

As mentioned before, some ‘historical waste’ from past activities may be stored or already disposed of in some countries. If this waste was not properly treated and conditioned in the past this may require its retrieval and reconditioning. Characterization of such historic waste is a difficult task. Such problems might have been avoided by adequate characterization, documentation and labeling of waste at the time of generation. This certainly contains a lesson with regard to future waste generation.

Methods of radioactive waste characterization and the methodology of characterization are described in detail in Ref. [18].

5.3.1.2. Collection and segregation

Collection involves the receipt of the waste from the waste generating processes and is followed by segregation if proper separation of waste streams is not part of the collection process. Segregation is an activity where waste or materials (radioactive or cleared) are separated or are kept separate according to radiological, chemical, biological and/or physical properties which will facilitate waste handling and/or processing. Segregation is the first consideration in planning and implementing a waste management technological system. The following are the main parameters in planning the segregation of waste:

- Physical, chemical and biological characteristics of the waste;
- Type and half-life of the radionuclides in the waste;
- Concentration of the radionuclides in the waste;
- Specifications or requirements to be fulfilled for further waste processing.

In general the efficiency or applicability of further waste processing must be considered in the selection of proper segregation strategies, for example separating compactible and not-compactible materials, or separation of long lived and short lived waste, etc.

Plans and procedures for segregation operations are generally custom designed to specific requirements but all necessary tools and equipment for waste handling, sorting and packaging are commercially available and normally not expensive.

5.3.1.3. Chemical adjustment

In some cases it may be necessary to adjust the chemical composition of liquid waste to ensure its compatibility with subsequent storage, treatment or immobilization processes. Although the chemistry of the reactions involved in most treatment processes is generally well understood and information is likely readily available, its translation into the facility and equipment which can be routinely operated or performed safely and in conformity with radiological protection standards is likely to require demonstration of the process on a significant scale and the application of special project engineering and design skills.

5.3.1.4. Physical adjustment

Physical adjustment is normally used for solid waste and usually involves size reduction such as dismantling of structures or components, cutting into pieces or shredding. This operation can be done on-site to meet transportation requirements or at a central waste processing facility to improve treatment performance. Basically these operations are not applied in countries with limited waste generation.

Physical pretreatment of liquid waste may include filtration of any fine particulates by precoat or sand bed filtration, which is essential before any effluent treatment by ion exchange.

5.3.1.5. Decontamination

There are different decontamination techniques which can be used to reduce the volume of solid waste by clearing some solid materials, however the generation of secondary waste and their subsequent treatment need to be considered.

5.3.1.6. Packaging

Packaging of radioactive waste by the waste generator for storage or transport to further waste processing is an important pretreatment operation. The waste to be transported has to comply with transport regulations, waste acceptance criteria or waste specifications for further waste processing, and with general occupational radiation protection standards.

The main features and limitations of the above pretreatment methods are shown in Table III. However, it should be pointed out that application of these pretreatment methods in class A, B and C countries may be rather limited.

5.3.2. Treatment

Treatment includes operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are:

- Volume reduction;
- Concentration of radionuclides into a small volume of the waste; and
- Change of composition.

After treatment, the waste may or may not be immobilized in course of conditioning to obtain an appropriate waste form. Different treatment and conditioning options for the waste from nuclear applications are described in Ref. [19].

5.3.2.1. Aqueous waste

In most cases treatment of aqueous waste aims at splitting it into two fractions:

(a) a small fraction of concentrate containing the bulk of radionuclides; and
(b) a large part, the level of contamination of which is sufficiently low to permit its discharge to the environment or recycle.

A treatment process cannot be assessed only for its ability to decontaminate the liquid waste stream and to concentrate radioactive contaminants. Treatment is part of an overall waste management process (see Fig. 3.) in which further conditioning and final disposal play an important role.

The selection of an aqueous waste treatment process involves a set of decisions related to a number of the factors described in Section 3. These factors could be grouped into five main categories:

- Up-front characterization of waste with the possibility of segregation;
- Availability of technologies for liquid waste processing and their costs;
- Discharge requirements for decontaminated liquids;
- Availability of technologies for conditioning of concentrates resulting from the treatment.
- Requirements for storage and disposal of the conditioned waste packages.

TABLE III. FEATURES AND LIMITATIONS OF SOME PRETREATMENT METHODS

Pretreatment methods	**Features**	**Limitations**
Frequently used methods		
Collection and segregation	• Enable waste characterization • Separate incompatible waste • Minimize radioactive waste volume • Enable recycle/reuse of material	• Additional dose for personnel • Requires sampling and monitoring
Chemical adjustment of liquid waste	• Neutralize and prepare liquid waste for treatment and encapsulation in a matrix • Destruct organics and corrosives that shorten package or equipment life	• Some technologies are too complex and/or expensive • Reagent addition may produce salts which are undesirable in some treatment methods
Physical adjustment of liquid waste (decantation, filtration)	• Easily applicable to aqueous waste and sludge • Remove organics • Remove fine particulates	• Secondary waste will be generated • No separation of dissolved materials • Processing of separate waste streams necessary
Physical adjustment of solid waste (size reduction)	• Enable use of one size of container for most applications • Reduce transport risk • Minimize volume of waste	• May not be applicable for small generators • Additional dose for personnel
Packaging	• Prevent spread of contamination • Enable handling and transport for treatment, conditioning, storage, and/or disposal	• Organic waste, including animal carcasses, must undergo additional treatment steps prior to disposal • Additional dose for personnel
Assay of radioactive content	• Waste classification and inventory for disposal • Segregation of waste for processing and disposal	• Some sophisticated methods and expensive equipment may be involved • Radioactive content may be changed in the course of further processing
Decontamination by manual cleaning	• Relatively low cost • Generation of small amount of secondary waste	• Slow process
Decontamination by chemical bath	• Suitable for different waste	• Chemically aggressive liquid secondary waste
Less frequently used methods		
Decontamination by vibratory cleaning	• Relatively large amount of secondary waste	• Applicable for large flat surfaces • Local ventilation needed
Decontamination by vacuum cleaning	• Small amount of secondary waste	• Applicable only for some types of contamination
Decontamination by electropolishing	• Small amount of secondary waste	• Applicable only for metallic objects • Slow process
Decontamination by ultrasonic cleaning	• Suitable for different waste	• Only for small amounts of waste

Treatment processes such as chemical precipitation, evaporation and ion exchange have been used for many years and they are well understood with regard to their main advantages and limitations. Other processes are not so well documented and demonstrated. Table IV [20] is a general guide showing the main features, including decontamination factor (DF) and limitations of some available treatment processes for aqueous waste.

Depending on the chemical and radiochemical composition of the waste and the extent of decontamination required, an optimum treatment method can be chosen. For example, if the waste is low in radioactivity, alkaline in pH and contains a significant salt load, chemical treatment, followed by separation of the sludge, would provide an adequate decontamination factor. This process is simple and relatively inexpensive in terms of the plant and its operation but it requires good understanding of the process chemistry and strict consideration of process parameters. The process may be limited by the activity level.

On the other hand, if the waste is relatively free of salts, and mildly acidic in pH and requires a decontamination factor of around 100 or so, ion exchange may be a good choice. This process is more expensive — especially when special purpose resins are used — but has a wider range of application with regard to radioactivity concentration. There could be situations when waste volumes are somewhat high, having a low salt content but a considerably higher activity level; in this event evaporation may be the right choice to reduce the waste volume to a concentrate and also to obtain a high decontamination factor (of the order of a few thousand). But the limitation here relates to the presence of radionuclides, which are more volatile; also the process is energy-intensive.

5.3.2.2. Organic liquid waste

The volume of organic liquid waste is small by comparison with aqueous radioactive waste, however, the risk associated with improper management of organics may be high. Aqueous waste may be discharged to the environment after the radioactivity has decayed or been removed by treatment. By contrast, organic radioactive waste requires management steps that not only take account of its radioactivity, but also of the chemical organic content since both can have detrimental effects on health and the environment. The 'dilute and disperse' option open for some aqueous and gaseous waste is not appropriate for most of organic liquid waste.

The main features of treatment methods for organic liquid waste [21] are summarized in Table V.

5.3.2.3. Solid waste

The essential purpose of solid waste treatment is to reduce the volume. The main features of solid waste treatment comprise waste pretreatment operations such as segregation according to activity and nature, packaging and size reduction, and final volume reduction. The available solid waste treatment options are described in detail in [22].

Table VI addresses the main features and limitations of most frequently used processes for solid waste treatment.

TABLE IV. MAIN FEATURES OF TREATMENT PROCESSES FOR AQUEOUS WASTE

Treatment processes	**Features**	**Limitations**
Frequently used methods		
Chemical precipitation (coagulation/flocculation/separation)	• Suitable for large volumes and high salt content waste • Easy industrial operations • Not expensive	• Generally lower DF than other processes ($10<DF<10^2$) • Efficiency depends on solid–liquid separation step
Organic ion exchange	• DF good on low salt content (10^2) • Good mechanical strength • Regenerable	• Limited radiation, thermal and chemical stability • Resins cost important • Immobilization difficulty
Inorganic ion exchange	• Chemical, thermal and radiation stability better than organic ion exchangers • Relatively easy immobilization • Large choice of products ensuring high selectivity • DF>10 to 10^4	• Affected by high salt content • Blockage problems • Possible high cost • Regeneration and recycling may be difficult
Evaporation	• DF>10^4 to 10^6 • Well established technology • High volume reduction factor • Suitable for a large number of radionuclides	• Process limitations (scaling, foaming, corrosion, volatility of certain radionuclides) • High operation costs • High capital costs
Solvent extraction	• Selectivity enables removal, recovery or recycle of actinides	• Organic material present in aqueous raffinate • Generates aqueous and organic secondary waste
Less frequently used methods		
Reverse osmosis	• Removes dissolved salts • DF 10^2–10^3 • Economical • Established for large scale operations	• High pressure system, limited by osmotic pressure • Non-backwashable, subject to fouling
Ultrafiltration	• Separation of dissolved salts from particulate and colloidal materials • Good chemical and radiation stability for inorganic membranes • Pressure < 1MPa	• Fouling-need for chemical cleaning and backflushing • Organic membranes subject to radiation damage
Microfiltration	• Low pressure operation (100–150 kPa) • High recovery (99%) • Excellent pretreatment stage • Low fouling when air backwash employed	• Backwash frequency can be high; depends on solid content of waste stream
Electrochemical	• Low energy consumption • Enhances the effectiveness of reactions	• Sensitive to impurities in waste stream • Ionic strength of waste stream can effect performance • Fouling is a problem above 10 g/L total solids

TABLE V. MAIN FEATURES OF THE LIQUID ORGANIC WASTE TREATMENT METHODS

Treatment methods	Features	Limitations
Incineration	• Decompose organic nature of waste • High volume reduction • Combined use for other waste • Eliminate infectious hazard	• Secondary waste must be treated • High temperatures are required to ensure complete decomposition • Off-gas filtration and monitoring are required
Emulsification	• Allow embedding of liquid organic waste into cement matrixes	• Low limits for content of emulsified liquids in the cement matrix
Absorption	• Solidify and immobilize organic liquids • Simple and cheap	• Suitable only for small amounts of waste • Absorbed waste may not meet disposal acceptance criteria
Phase separation (e.g., solvent extraction)	• Remove water and detoxifies the waste for direct disposal • Produce clean solvent	• Non-universal application. • Technology is relatively expensive for this type of waste
Wet oxidation	• Low temperature process • Simpler than incineration • Suitable for biological waste	• Requires storage of oxidizing agent • Residue requires immobilization

TABLE VI. MAIN FEATURES OF THE SOLID WASTE TREATMENT PROCESSES

Treatment methods	Features	Limitations
Frequently used methods		
Size reduction • Shredding • Dismantling • Cutting	• Usually performed during pretreatment, may be optimal during treatment • Applies to metals when decontamination is not successful	• Requires large equipment, expensive to maintain • Economically may not be justified for small amounts of large items
Low force compaction	• Relatively low cost • Easy to operate	• Low volume reduction factor (3–5)
Frequently used methods, but more expensive		
High force compaction	• High volume reduction factor (up to 100) • Good quality waste form • Services may be exported to other Member States	• High equipment cost • Maintenance is costly and frequently required
Thermal destruction (incineration) • Excess air • Controlled air • Pyrolysis • Fluidized bed • Slagging • Rotary kiln	• High volume reduction factor • Ranging from low technology to high technology, matching the need of the user	• High equipment and operating cost • Off-gases must be treated and • Trained workforce is required • Ashes resulting from incineration require immobilization in a stable integrity matrix (e.g., cement)
Chemical decomposition	• Avoids the necessity of high temperature incineration • Suitable for biological waste in small scale	• No volume reduction

5.3.2.4. Biological/infectious waste

Biological waste if left untreated, will decompose and liquefy, and therefore increase the possibility to enter the biosphere. When processing biological wastes, their infectious features, tendency to putrefaction, to insect attacks and to microbial degradation must be controlled. Further to radiological protection, other precautions for handling these wastes should be respected [23, 24].

Lidded containers lined with plastic bags are used for collection of wastes displaying biological hazards, special consideration should be given to sharp objects. When possible, these items should be collected in puncture resistant packages, properly labelled and treated separately.

Processing of biological solid wastes starts with neutralization of their biohazardous components by thermal or chemical treatment. This could be done by steam sterilization, dry heat sterilization, microwave sterilization, chemical disinfections or intensive gamma irradiation. While steam and dry heat are regularly used in hospitals and appliances, other methods require special equipment or skilled personnel and aggressive chemicals. In all cases the pre-treated items should be of size allowing their sterilization throughout the whole matter (e.g. not larger then a rabbit carcass).

Limitations and features of the waste treatment methods applied for biological radioactive waste [23] are summarized in Table VII.

TABLE VII. MAIN FEATURES OF BIOLOGICAL WASTE TREATMENT METHODS

Treatment method	**Features**	**Limitations**
Frequently used methods		
Incineration	• Effective reduction of the toxicity, mobility, and volume of several types of waste • Inexpensive if used jointly with the available incinerator for other waste	• Is justified only if the volume of waste generated is rather high
Chemical modification – mummification – desiccation	• Prevent decomposition and putrefaction • Commonly practiced	• Some toxic solutions may be required
Sterilization – steam – dry heat	• Regularly used in many facilities	• Special equipment needed
Maceration/pulverization	• Change the physical form	• Secondary waste still require treatment and conditioning
Freeze drying	• Remove liquids and leaves the solid waste for disposal	• Difficulties with large carcasses • Requires rather expensive equipment
Less frequently used methods		
Sterilization by microwaves	• Equipment widely available	• Trained workforce is required
Chemical disinfections	• Easy to use • Low cost for equipment	• Aggressive chemicals used
Intensive gamma irradiation	• Easy to use for different waste	• Applicable only for small size objects • High equipment cost

5.3.2.5. Airborne waste

Ventilation and air cleaning systems are a vital part of the general design of any nuclear facility. The combination of a well designed ventilation system with thorough cleaning of exhaust air is the main method of preventing radioactive contamination of the air in working areas and in the surrounding atmosphere. Ventilation and cleaning should provide efficient cleaning under normal operations, maintenance and accident conditions.

Ventilation systems are multifunctional. They provide operator protection by maintaining the required depressions and flows in various sections of the facility and, by collecting contaminated airflows they control (by filtration and measurement) airborne activity which could be released from the facility. Among typical ventilation system elements are fume hoods and fume cupboards, glove boxes, fans, silencers and dampers, which are connected by piping in such a way that inward air flow is maintained through all leakage paths to the atmosphere.

For routine releases of radioactive materials into the environment, the main effluent control options are to provide either delay tanks for gaseous effluents (so that short lived radionuclides can decay before release), or treatment facilities which remove radionuclides from the effluent stream for disposal by other means. More frequently a filtration system is used for removing radionuclides from the exhaust airflows. HEPA filters are used for removal of aerosols, and sorption filters (charcoal based) for removal of noble gases and iodine. In order to extend the lifetime of HEPA filters, prefilters are used to remove heavy dust concentrations and extraneous materials.

Design and operation of off-gas cleaning and ventilation systems in facilities handling low and intermediate level radioactive material are described in detail in Ref. [25].

5.3.2.6. Secondary waste

Pretreatment and treatment of radioactive waste usually generate secondary waste. This secondary waste may result from the treatment process itself; from maintenance, repair or replacement of spent media or parts; or from dismantling of components of the plant. The secondary waste may be in solid, liquid and (less frequently) gaseous phases.

Secondary waste is often of a nature similar to the primary waste and, therefore, can be treated by the same or similar methods. In some instances, however, secondary waste may be quite unique (e.g. incineration ash) and may require a different treatment method.

Evaluation of the secondary waste amounts and characteristics as well as the choice of its treatment methods is an essential step that should never be omitted or underestimated during the planning stage. Results of this evaluation could significantly affect the overall volume reduction factor, economics of operation, or even selection of the primary treatment process itself.

5.3.3. Conditioning

Conditioning includes those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, additional immobilization of some solid waste, packaging of the waste form into containers, and, if necessary, providing an overpack. The *waste form* is the waste in its physical and chemical form after treatment and/or immobilization (resulting in a solid product) prior to packaging. The waste form is a component of the waste package.

The *immobilization* of radioactive waste (solidification, embedding or encapsulation) to obtain a stable waste form is an important step in waste management needed to minimize the potential for migration or dispersion of radionuclides into the environment during storage, handling, transport and disposal. A number of matrices have been used for waste immobilization and include glass, ceramic, cement, polymer and bitumen [26–30]. All these matrices have their advantages and disadvantages both in terms of the kinds of waste that can be immobilized and the properties of the solidified waste forms obtained.

The choice of the immobilization matrix depends on the physical and chemical nature of the waste and the acceptance criteria for the disposal facility to which the waste will be consigned. Table VIII indicates the relative merits of a number of the different matrices used for immobilization of low and intermediate level radioactive waste.

TABLE VIII. IMMOBILIZATION OPTIONS FOR LOW AND INTERMEDIATE LEVEL WASTE

Features	Cement	Polymer	Bitumen
Process			
Complexity	Low	High	High
Flexibility	High	Average	High
Volume reduction	Negative	Negative	Positive
Cost	Low	High	High
Waste form			
Compatibility with waste streams	Average	Average	High
Waste loading	Average	High	High
Compressive strength	High	Average	Low
Impact resistance	High	Average	Average
Fire resistance	High	Average	Low
Radiation stability	High	Average	Average
Retention of radionuclides			
* actinides	High	Low	Low
* non-actinides	Low	High	High

The *waste package* is the product that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal. These requirements can be different for each step indicated above or they can be combined in one set of parameters that combine conservative requirements for each step. These requirements are often called waste acceptance criteria (WAC) and they constitute an agreement among the waste generator, transport organization, and waste disposal facility operator regarding the minimum characteristics of each waste package and internal barriers, e.g. absorbing materials, liners. WAC are imposed on the waste operator by the regulatory body or by the operator of the disposal facility.

Waste packages are often produced when no disposal facility exists and therefore no applicable disposal WAC are available to guide the design and preparation of the packages. In this case, it may be necessary to develop waste package specifications in place of the WAC. These specifications are considered as a design output, and are intended to control the radiological, physical, and chemical characteristics of the waste package to be produced. Waste specifications are usually oriented towards the performance or control of specific facility processes and may be used as a contractual vehicle to control subcontracted operations. Waste specifications, like the WAC, should be cognizant of intended storage/disposal facility parameters and transport regulations, and incorporate relevant parameters of the WAC, or in lieu of the WAC, when they have not been developed.

It should be noted that the requirements on waste packages imposed by the IAEA transport regulations meet many of basic requirements of the generic WAC.

5.3.4. Storage

Storage is an integral part of the waste management process and should be provided for conditioned waste as well as for untreated/unconditioned (raw) waste.

Storage for unconditioned waste is needed for decay of short lived radionuclides or for collecting the waste before transferring for treatment and conditioning. Storage for decay is particularly important for radioactive waste resulting from medical uses of radioisotopes since many radioisotopes are short lived and the activity of the waste produced is well defined. Practical experience shows that on-site decay storage is suitable for waste contaminated with radionuclides with a half-life up to l00 days. Particularly where large volumes of biomedical radioactive wastes are produced, it may be more convenient to partition the short term decay storage facility to provide areas for storage of wastes according to their half-life.

The main functions of a storage facility for conditioned radioactive waste are to provide safe custody of the waste packages and to protect both operators and the general public from radiological hazards associated with radioactive waste in storage. While storage of conditioned waste is normally described as a temporary measure, for some Member States this may become fairly long term until a repository becomes available.

The design of storage facilities has to meet national regulatory standards and basic safety principles and should aim to reduce the probability of accidents to a level as low as practicable. In this context, the facility should be capable of maintaining the ‘as-received’ integrity of the waste package until it is retrieved for disposal. The storage facility must protect the waste from environmental conditions, including extremes of humidity, heat and cold, or any other environmental condition, which would degrade the waste form or container. Local climatic conditions may result in the need for cooling or dehumidifying of the store atmosphere, in order to avoid possible deterioration of the waste packages.

Safety requirements mandate external dose rate and contamination limits for waste packages to be accepted by the storage facility. In other respects the storage facility usually adheres to the waste acceptance requirements of the disposal facility.

In general, design criteria for any storage facility should take into account the following considerations:

(a) Acceptance of the maximum operational holdings anticipated from the waste generating facilities;
(b) Acceptance of the waste from another storage unit whose integrity may be breached or suspect;
(c) Availability of appropriate equipment for handling waste packages;
(d) Prevention or restriction of degradation of waste packages and dispersion of radioactivity;
(e) Provision of adequate environmental conditions (heating, cooling, humidity control) to ensure proper conservation of waste packages during their tenure at the facility;
(f) Provision for fire protection where combustible waste is present;
(g) Provision for gas dissipation if gas generation is anticipated;
(h) Segregation of waste according to its hazard level and, if possible, based on the disposal route;
(i) Clear identification of stored waste packages and record keeping should be provided;
(j) Simplification of inspections and monitoring of stored waste;
(k) Retrieval of stored packages;
(l) Prevention of unauthorized access.

As far as the siting of a storage facility is concerned, it should be situated above the groundwater level, and certainly not in a flood plain. In areas of high rainfall, the facility should be constructed with appropriate systems to protect against intrusion of groundwater.

Waste storage facilities vary from a simple steel safe to a sophisticated engineered facility [31].

5.4. MANAGEMENT OF DISUSED SEALED RADIOACTIVE SOURCES

The management of disused radioactive sources includes the following activities (See Fig. 4) [31]:

- identification;
- collection and transportation; and then
- either return to the suppler or another user; or conditioning;
- storage;
- disposal.

Return of disused sealed sources to the supplier should be a preferred option. High activity sources used for sterilization and irradiation should always be sent back to the supplier. The supplier has better possibilities to reuse the radioactive material. Further, a supplier is normally better equipped with technologies and appliances, such as remotely controlled handling cells and systems and waste management facilities, allowing safe and economically effective processing of the sources. Most new contracts for the purchase of sources contain a clause for the return of the sources once they are disused. This method is, however, not available for many old sources as the original supplier is unknown or no longer exists. Also, financial constraints have, in some cases, hindered the return of disused sources as the cost of packaging and transportation may be considerable.

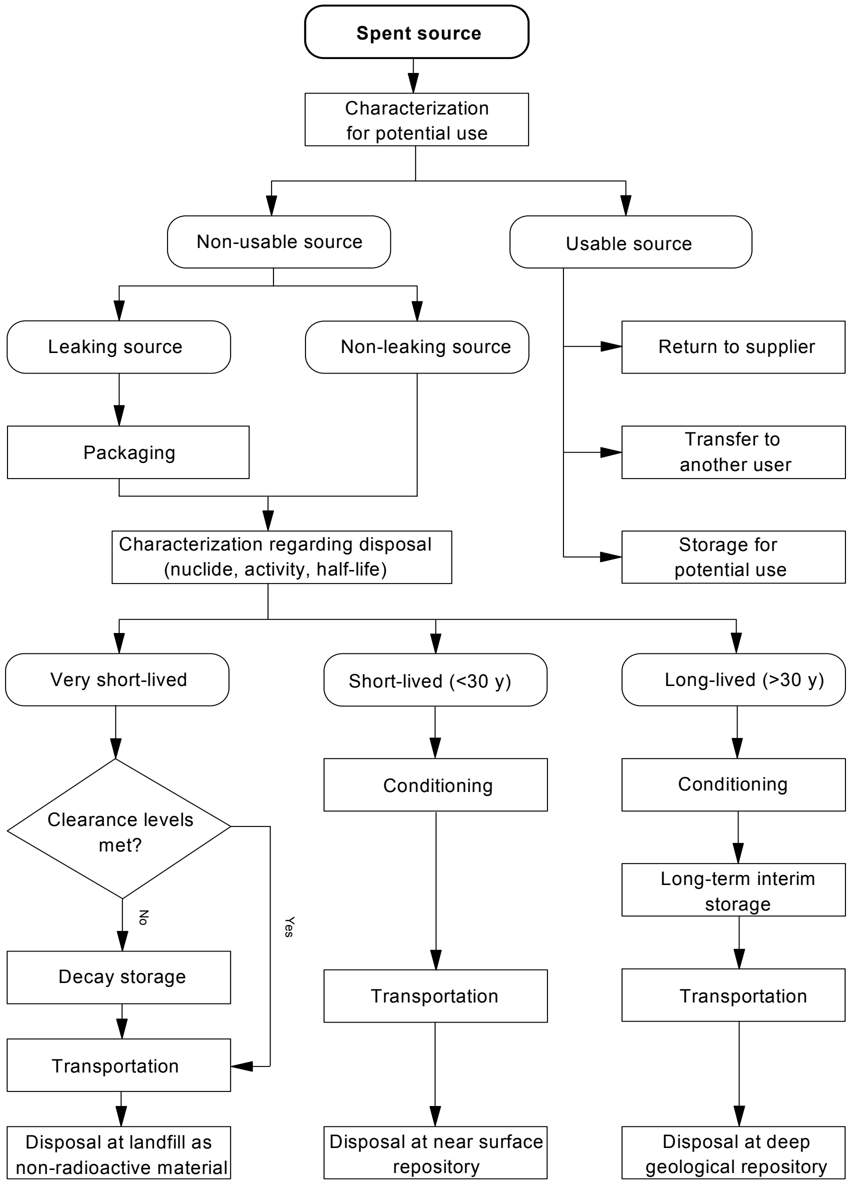

FIG.4. Management of disused sealed sources.

Disused sealed sources which cannot be returned to a supplier or to another user should, without delay, be:

- packed into a container minimizing their radiation hazards;
- (if very short lived) transferred to a storage facility and stored for decay until clearance levels are reached, or
- (if long lived) conditioned in such a way that the source is made safe and then transferred to a proper store while awaiting eventual disposal. Conditioning can be carried out either on-site or at a specific conditioning facility.

The simplest way of conditioning of disused sealed radioactive sources consists of grouting the source (or sources — depending on their activity) in drums as described in [31]. However, encapsulation of disused sealed sources in an irretrievable form (e.g., by direct encapsulation in cement) may complicate future handling of the waste. Encapsulation of sources in containers that are large or varied in size may have negative impacts on transport, storage, or disposal.

A particular problem exists with the disposal of disused sealed sources. Existing near surface repositories normally do not accept conditioned disused sealed sources for disposal because those do not comply with the waste acceptance criteria: the concentration of radionuclides is too high, and it is not distributed homogeneously within the waste package.

6. SELECTION OF AN EFFICIENT ORGANIZATIONAL SYSTEM AND TECHNOLOGIES FOR WASTE PROCESSING AND STORAGE

The objective of this section is to provide practical advice to managers and decision-makers in class A, B and C countries engaged in establishing or revising the national system for management of radioactive waste. Recognizing the fact that there are large differences in the needs of individual countries even within the same group, the ambition is not to give advice, which is directly applicable to all individual countries at all situations. However, it is expected that the advice given below will be applicable in most cases.

The following sub-sections give generally applicable advice on organizational, administrative and technological issues relevant to all countries. Management of disused sealed sources is very specific and less dependent on the class of countries and is therefore dealt with in a separate sub-section. Finally there are specific suggestions on the system for the three classes of countries concerned. It should be recognized that there are individual countries, which have specific waste streams or other country-specific situations which may justify other options than those suggested below.

6.1. ORGANISATION OF WASTE MANAGEMENT

6.1.1. Legal framework

Safe management of radioactive waste requires a sound legal base comprised of primary and subordinate legislation (laws and regulations). Depending on the state of the nuclear applications and corresponding waste management activities the requirements for radioactive waste management might be set up in a special law or included in an appropriate law, e.g. on radiation protection, environment protection, health care, etc. The details provided in a law should be kept to a minimum, preferably only the framework should be provided along with provisions for issuing subordinate legislation.

It is assumed that class A countries, which are only using radioactive material at one or very few places, will not require a special waste management regulation, although the availability of such a regulation is obviously advantageous.

Safe management of radioactive waste requires that an administrative framework be established to implement the law. The work of administration is normally done by staff who belong to either a regulatory body or an implementing organization. The law also normally identifies the Ministry or Department responsible for appointing a regulatory body which is authorized to implement the law, and should also highlight the regulatory body's most important functions. The law should give the right to the regulatory body to issue subordinate legislation (the waste management regulation) in support of the law, if necessary.

The law should also identify the responsibility for the implementation of radioactive waste management activities, which normally lies with the waste generator. However, in case of rather intensive waste generation in the country there is also need to appoint a central waste management operator who can manage all the waste that cannot be treated at the place where it is generated.

The legal basis for waste disposal should be outlined, the details of which should be given in a regulation. The responsibility for waste disposal should also be addressed.

6.1.2. Regulatory body

In Member States with rather limited nuclear activities regulatory functions on radioactive waste management may be delegated to an existing governmental organization responsible for protection of workers, the general public and the environment, such as Ministry of Health, Ministry of Natural Resources and Environmental Protection, Ministry of Education and Industrial Development, etc. The practical regulatory function could be assigned to a special branch of these governmental organizations with a limited number of staff. However, this staff should possess the necessary educational background and appropriate training to implement their duties in accordance with internationally accepted practices and approved national requirements. This body represents an important link between State requirements and operators who generate (by using radioactive materials) radioactive waste and operate waste management facilities.

The regulatory body's role in regulation of waste management is to ensure the required level of safety to protect of man and the environment throughout the entire life cycle of the waste from waste arising through collection, treatment and storage until final disposal One of the important responsibilities of the regulatory body is to control all steps and components of the waste management system in order to ensure that the identified objectives are met in a most efficient and effective way.

6.1.3. Waste management operator

The organizations implementing waste management operations range from operators that use radioactive materials and generate radioactive waste to specialized facilities, which collect waste from the waste generators for centralized processing, storage and disposal. Efficient operation of waste processing requires the availability of sufficient equipment and technology, well educated and trained personnel and adequate provision of financial and other resources.

In Member States with limited waste generation and financial resources, provision of all of the above components may be rather difficult. Therefore resources allocated for waste management practices should be utilized with maximum care to develop and maintain the system, which should be effective in terms of economy and sufficient safety requirements. Such a system could be developed only if all its components are adequately considered and evaluated in terms of integrity, technical capacity and reasonable sufficiency.

Where there are many waste generators and large volumes of diversified waste are generated (class B and C countries), there is an advantage to establish centralized waste management. Depending on the national situation, centralized waste management can be done by a major waste generator, by a service organization, or by a specialized waste management organization. In countries where the national regulatory system is not very well developed, the waste management organization should be a State organization or a public company. In special cases the service of a foreign organization, inside or outside the country, specialized in waste management can be considered. It may also be possible to use the services of companies which are normally working with the equipment containing sealed radioactive sources and which have capacities for managing disused sources.

In countries with a nuclear research center the best national waste management competence is often available at the center and the country should seriously consider to use this competence within a national waste management system, for example by using the research center as the central waste management organization. Alternatively the research center can be an adviser to a specially established waste management organization or provide specialized services for that organization.

Initial management of radioactive waste should always be done at the site of waste generation. The initial steps include collection, characterization, segregation, documentation and normally also decay storage.

Waste containing short lived radionuclides is processed on-site by decay storage during a limited period of time. An exception may be the waste from medical applications which due to some non-radiological hazards (infectious properties, chemical and biochemical toxicity) may requires special treatment, which may be done on site or at the centralized waste processing facility. Long lived waste requires centralized treatment and long term storage until an appropriate disposal option for this kind of waste is available. Long distance transport of untreated waste may also justify on-site processing. However, a particular decision or a solution should be made in each particular case taking into account specific local conditions.

Decay storage should be arranged at the site of waste generation since the waste generator has best knowledge of his waste, and transport of unconditioned waste in principle is more risky than transport of conditioned waste. However, there might be cases where transportation of the waste intended for extended decay storage outside the place of generation could be justified. Generally, for the radioactive material considered for clearance the decay storage time should not extend two years, but in the case of creating very good storage conditions (including physical protection), the storage time might be extended. This may be relevant for the decay of ^{192}Ir sealed sources ($T_{1/2}$ = 74 d). Materials intended for decay storage may need some pretreatment, such as adjustment of pH or size reduction.

Any processing of radioactive waste requires investments both in a form of software (education and training of personnel, development of procedures, etc.) and hardware (equipment, tools, building, etc.). When the waste needing processing is generated at many places it is not efficient to make investments for this purpose at all these places. The preferred solution would be to establish a comprehensive waste processing system at a central facility leaving necessary pretreatment to the waste generators. The use of standardized containers for the conditioned waste may increase the efficiency of the waste processing system. However, it may be justified to have special treatment and/or conditioning at some waste generators where large quantities of waste or unique waste streams are generated. It may also be justified to use the support from a central facility (e.g. in the form of mobile facilities) at the remote waste generating sites. Safety assessments should verify the chosen option.

Since the establishment of a licensed repository may take very long time, an interim waste store should be designed and constructed to create safe custody for radioactive waste for at least a few decades. The store has to meet high safety and design requirements including maintenance, record keeping and physical protection [30]. All these requirements will add to the cost, which implies that this type of store will be established only at one or a few places in a country.

6.1.4. Clearance and authorized discharges

As discussed in Subsection 2.2.2.6, clearance of radioactive material is needed to avoid unnecessary accumulation of radioactive waste and to save significant financial resources. For countries, which have no legal base for clearing radioactive material, an urgent task is to have them established. If a country experiences difficulties in deriving clearance levels, the IAEA-TECDOC-1000 on Clearance of Materials Resulting from the Use of Radionuclides in Medicine, Industry and Research [12] or the exemption levels published in the BSS [8] may be used for small quantities of waste. Decommissioning of large research reactors may generate such quantities of waste that the exemption levels in BSS may be too high for safe clearance.

Supplementary to the clearance mechanism, the legal system should permit authorization of discharges and releases based on site-specific analysis especially to make it possible to handle gaseous radioactive material and significant volumes of very low contaminated liquids.

Some special waste types with low activity content, which are difficult or expensive to treat as radioactive waste, may sometimes be treated together with other types of hazardous waste. For example, small quantities of biological and pathogenic waste as well as organic liquid low level waste can be incinerated in existing incinerators, for example used for municipal, toxic or medical waste. For such practices, the waste generator should prepare a safety assessment, which demonstrates that it can be done safely. It is, however, recognized that such facilities may not exist in many countries and that facilities may not accept radioactive waste. If regularly used, formal legal procedures for authorization of the practice could be implemented. Methodologies for such procedures can be found in Ref. [12].

6.1.5. Transport of conditioned and unconditioned waste

The form of radioactive waste to be transported has a large impact on the safety of transport operations. When the waste form is solid and homogenous, there is only a small risk for dispersion of the material even if the package is broken, while for instance liquid waste will be dispersed easily. Therefore for the approval of unconditioned waste transportation there are stricter requirements on the strength of the containers. This makes such containers more expensive and they may not be available in all countries.

It is always possible to make transportation under ‘special arrangement’, but in that case it has to be demonstrated to the authority that the total safety of the transport is not less than of the transport under standard arrangements. One of the special precautions normally used is dedicated transportation (only for specific radioactive material), where in the case of transportation by car, at least one other car with a qualified radiation protection officer equipped with necessary instruments and tools to be used in the case of an accident should accompany it.

6.1.6. Financing waste management

Although the general principle for financing waste management is ‘the polluter pays’, the countries concerned generally have no system for financing waste management purposes. Most of the use of radioactive materials are in the public sector and therefore the cost of waste management will be eventually taken from the public sector. For this reason it would be in most cases practical to finance national waste management activities via the State budget rather than establishing an expensive administrative system for fund-raising from the waste producers. However, as the main radioactive material is imported in most countries, it may be possible for the State to at least partly cover its cost for waste management by import taxes/fees on radioactive material.

6.2. PROCESSING TECHNOLOGIES

6.2.1. Segregation

The main objective of waste management processing is the conversion of the radioactive material, for which no further use is foreseen, into a form that is suitable for storage and eventual disposal.

Segregation of waste into groups suitable for further processing should always be done as soon as possible after generation of the waste. It is of special importance to separate material, which can be cleared immediately or after decay storage. Aqueous waste should be kept separated from organic liquids, and liquid waste coming from different sources should, if they have different characteristics, not be mixed without careful consideration of the consequences.

6.2.2. Treatment of solid waste

In most cases the quantities of solid waste generated is so small that volume reduction is not a major objective although it might be justified in some central waste management facilities to introduce a simple and cheap volume reduction technique in the form of in-drum compaction and mechanical tools for cutting large pieces into small ones suitable for packing in standardized waste containers.

6.2.3. Treatment of liquid waste

In many cases, especially in class A and B countries, the quantities of liquid waste generated are small enough to justify any treatment. Some volume reduction or treatment of some special waste categories could be obtained by using laboratory scale equipment (e.g. for distillation of both aqueous and organic liquids, liquid–liquid extraction, chemical precipitation, ion exchange technique, wet oxidation). No technique should be used for which there are no qualified experts at the laboratory to set up and operate the system and fully understand its function.

Only at centralized waste management facilities and/or at nuclear research centers with a large research reactor, could it be justified to establish full-scale treatment facilities. Considering the difficulties and risks with transportation of liquid waste, solidification of the waste at the site of the waste generator, e.g. by absorbing the liquid in a suitable absorber should be assessed. If liquids need to be transported, their packaging must be done with great care.

The time for storage of liquid waste should be kept as short as practicable considering the risks associated with dispersal of radionuclides.

6.2.4. Treatment of gaseous waste

Treatment of gaseous waste is justified only in special cases, like, for example, in research reactors, radioisotope production, labeling with radioactive iodine isotopes and research using very radiotoxic isotopes. Thus, normally the gaseous waste generated during a practice is vented to the environment immediately upon generation. The consequences of this release should be assessed when licensing the practice giving rise to the gaseous waste. Therefore a legal base should be exist on authorized discharges which can support these actions.

6.2.5. Treatment of biological and infectious waste

In case of generation of biological and/or infectious waste, these can be managed by standard methods for preservation of biological material and disinfecting. Urine and faeces from patients subjecting to diagnosis or medical treatment with radionuclides can normally be discharged after proper dilution in the normal sewage system of the hospital. For therapy patients special toilets with decay tanks should be used which can be regularly controlled for contamination.

6.2.6. Conditioning

For most aqueous waste and disused sealed radioactive sources cementation is most suitable and adequate method for incorporation or encapsulation of the waste generated in class A, B and C countries. The main reasons for using cementation processes are:

- relative simplicity of handling;
- extensive experience in civil engineering operations;
- availability of raw material;
- relatively low cost;
- high density (shielding) and mechanical strength of resulting waste forms;
- compatibility of wide range of waste with matrix material.

The cementation process for radioactive waste immobilization, with and without additives, has been commonly used on an industrial scale for several tens of years in different countries [28]. For the preparation of cement grout or concrete a very simple mixing machine can be applied.

6.2.7. Historical waste

Historical waste is the radioactive waste, which had been generated in a country during the past and managed in a way, which is not in agreement with current requirements. Further its characteristics may have changed as a result of improper conditioning and storage. Unidentified spent sealed sources may have been accumulated at the user facility. The identification of such sources could be accomplished by either gamma spectroscopy or appropriate radiation detectors.

Retrieval and reconditioning of historical waste is an operation that may require the development of special tools and techniques, which do not exist. Additional complications are the poor characterization and documentation of the historical waste. International experience from such operation exists and should be used.

6.3. MANAGEMENT OF DISUSED SEALED SOURCES

The problems associated with the management of disused sealed radioactive sources and the practical solution of these problems are likely to exist irrespective of the total generation of radioactive waste. There are the same three options for the back-end of disused sources as for other waste: clearance, disposal in a near surface repository and disposal in a geological repository. Due to the characteristics of sealed sources, only rather low activity sealed sources can be disposed of in near surface repositories and therefore there might be a relatively large part of the sources which need disposal in a deep repository. Such a repository, however, is unlikely to be established in countries other than those having high level waste and/or spent nuclear fuel from nuclear power reactors. Alternatively special regional repositories for spent sealed sources could be used if an agreement is reached for their establishment.

In the countries concerned, the preferred option for the management of disused sealed sources, which cannot be cleared after decay, is to return the sources to the supplier. Arrangements for the return should be made in advance when purchasing the sources. The return should also be considered in the case of sources obtained by donation. Even for old disused sources all efforts should be made to return them to the original supplier. Due consideration should be given to the limitations imposed by the Joint Convention [10] and other legally binding legal instruments.

The sources requiring disposal that cannot be exported to a country capable of their proper management should be conditioned as soon as possible in order to reduce the risks associated with such sources (many disused sources are disappearing from their storage places due to a mistake or illegal acts and later cause unnecessary exposure to innocent people).

Disused sources that can be disposed of in a near surface repository can normally be conditioned in a rather simple way, for example with concrete in a standard 200 L steel drum.

Conditioning of the sources to be disposed of in deep repositories should not compromise compliance with the future waste acceptance criteria. These conditioning operations are rather complicated and require sophisticated equipment and trained personnel. Countries which, for one reason or another, cannot undertake such an operation should seek assistance from abroad. The IAEA has, for example, a special technical co-operation project for conditioning of radium sources in developing countries.

Table IX summarizes the preferred options for disused sources and gives alternative options for particular cases.

TABLE IX. INDICATION OF PREFERRED OPTIONS FOR THE MANAGEMENT OF DISUSED SEALED SOURCES[a]

Half life	Activity Bq	Preferred option		Alternative option	
		Processing	Final step	Processing	Final step
<100 d	All	Decay	Clearance	Conditioning in a standard waste package	Disposal in a near surface repository
>100 d <30 a	$<10^6$	Conditioning in a standard waste package	Disposal in a near surface repository	Packaging for transport	Return to the supplier (or other export)
>100d <30 a	$>10^6$	Packaging for transport	Return to the supplier (or other export)	Conditioning in a special waste package	Disposal in a deep repository
>30 a	$<10^3$	Conditioning in a standard waste package	Disposal in a near surface repository	Packaging for transport	Return to the supplier (or other export)
>30 a	$>10^3$	Packaging for transport	Return to the supplier (or other export)	Conditioning in a special waste package	Disposal in a deep repository

[a]There might be exceptions in special cases.

6.4. MANAGEMENT OF WASTE IN CLASS A COUNTRIES

In class A countries usually there are a few waste generators and small quantities of waste generated that does not justify establishment of a special waste management organization outside organizations generating the waste. In this situation, the authority should give the proper recognition of the waste generator as the waste management operator. If there is inadequate competence of any waste generator to properly manage the waste, it might be justified for the radiation protection authority, which entails basic waste management competence, to undertake the necessary waste management activities following the initial steps, which always should be done by the waste generators.

6.4.1. Waste storage

Unconditioned sealed and unsealed sources and some waste may require some storage space at the waste generation site (hospital or medical facility, etc.). This space could be provided in a locked room. Conditioned spent sources and waste should be stored in a separate locked room, or outside in a locked metal shipping container that is used for sea, road or rail transportation [32].

6.4.2. Solid waste

Solid waste should be collected at the places of its generation, and segregated into waste for decay storage, clearance, which is the largest part, and waste for interim storage. The waste for clearance can normally decay in the containers in which it is collected. Therefore, it only requires monitoring and administrative procedures like record keeping.

The waste for storage should be put into a container appropriate for extended storage. Encapsulation with cement directly in the waste container (usually 200 L drums) is the suggested conditioning option.

6.4.3. Liquid waste

Most aqueous waste can be discharged via the sewage system either as cleared waste or within an authorized limit. The small remaining liquid is recommended to be absorbed by a commonly used material (e.g. silica gel, activated charcoal) followed by encapsulation with cement in a standard waste container (200 L drum) together with solid waste.

Small quantities of organic liquid waste, e.g. liquid scintillation cocktails, can be either cleared or absorbed, for example, on the activated charcoal and immobilized together with solid waste into a cement matrix.

6.4.4. Gaseous waste

No treatment is normally needed except standard ventilation.

6.4.5. Waste management equipment

Examples of the equipment that is necessary for safe handling, processing and storage of radioactive waste in class A countries are shown in Table X.

TABLE X. EQUIPMENT NEEDED FOR THE MANAGEMENT OF WASTE GENERATED IN CLASS A COUNTRIES

Management steps	Equipment, tools, materials or facilities	Remarks
Identification and characterization	• Dose rate monitor • Contamination monitor • Portable gamma spectrometer • Long tongs • Basic radiation protection equipment	This instrument can be rented for measurement and for handling of waste
Collection and segregation	• Plastic bags • Refuse cans	10–50 pieces
Decontamination	Tissues, cotton, detergents, masks, protective clothing	Secondary waste should be conditioned together with other solid waste
Conditioning	• Silica gel, activated charcoal • Shovels, etc. for manual cement–water–sand mixing • Cement, sand, water • Steel drums (200 L)	Standard hardware items
Handling and storage	• Simple lifting device • Building, room or shipping container	Lifting capacity 500 kg
Transport	Container Type A or Type B as required [14]	

6.4.6. Quality assurance

There is no requirement in class A countries to establish and implement a formal quality assurance programme. However, the waste generator is responsible for monitoring, documentation and record keeping of the waste generated, cleared, stored and disposed of. A record of the completion of the procedures must also be kept along with information on the contents of the waste package prepared for extended storage. In particular, the following information must be recorded:

- Description of the contents of the waste container;
- Type of radionuclides present and their activities;
- Date of activity measurement;
- Date of conditioning, as relevant;
- Surface dose rate;
- Physical data, such as weight and volume.

6.5. MANAGEMENT OF WASTE IN CLASS B COUNTRIES

6.5.1. General approach

The waste management practices and procedures in class B countries are the same as in class A countries, however, because of a larger number of waste generators, one of the waste generating facilities might be designated as a central waste processing and storage facility. It would lead to cost savings in providing all of the radiological measurement instrumentation and qualified staff at one selected facility only.

6.5.2. Solid waste

Solid waste should be collected at the places of its generation and segregated into waste for clearance, which is the largest part, and waste for interim storage, the latter which might require further segregation. The waste for clearance can normally decay in the container in which it is collected. In the facilities where different waste streams are generated, arrangements should be made for collection of the waste with similar characteristics and decay requirements. Thus, it requires more precise monitoring and administrative procedures (especially good record keeping) compared with similar activities in class A countries.

The waste for centralized interim storage should be put into standard waste containers and preferably conditioned at the place of generation by direct encapsulation with cement in a waste container. Transportation of treated but not conditioned waste can be arranged if the packages with unconditioned waste meet the transport requirements, in particular for transport of low specific activity (LSA) or surface contaminated objects (SCO). Such transport should be available and be provided by the central waste management organization.

In countries generating few cubic meters of solid waste or more, it can be justified to install an in-drum compactor for solid waste. If so, there should not be any cementation of the compactable solid waste at the waste generator site.

At the central interim storage facility, arrangements should be made for separate storage of waste packages with different characteristics due to possible different routes of such waste for final disposal.

During decommissioning of facilities, contaminated as a result of normal operations or from an accident, significant quantities of solid waste will be generated during a relatively short period. In most cases the existing waste processing facilities will be capable of handling this decommissioning waste, but there might be the need for size reduction and handling of building material which normally is not done at the site.

6.5.3. Liquid waste

The significant part of aqueous waste can be discharged via the sewage system either as cleared waste or within authorized discharge limits. The remaining aqueous waste should be directly conditioned by cementation in a standard waste container if the arising is less than one cubic meter per year. If more, conventional waste treatment methods should be introduced e.g. ion exchange technique or chemical precipitation. Ion exchange resins used for absorption and/or adsorption should be directly cemented in standard waste containers. Chemical precipitation requires more difficult handling of the resulting sludge in order to have it conditioned. The question of whether the treatment should be made at the place of generation or at a central facility needs to be assessed on a case-by case basis. Relatively simple treatment of liquid waste at the place of generation may substantially reduce its volume and need for transport.

The small quantities of organic liquid waste, e.g. liquid scintillation cocktails, expected in class B countries, can be either cleared or absorbed for example on activated charcoal and conditioned together with solid waste.

6.5.4. Waste management equipment

Additional equipment that is necessary for handling, processing and storage of radioactive waste in class B countries are shown in Table XI. In principle, the equipment, tools and materials used are the same as for class A countries, however the use of more efficient waste conditioning equipment, such as a motor driven cement mixer in place of manual cement mixers is recommended. Greater volumes of conditioned sealed sources will require a larger storage facility than for class B countries.

6.5.5. Quality assurance

For class B countries there is also no requirement for a formal quality assurance programme. The waste generator has all the responsibility for monitoring, documentation and record keeping of the waste generated, cleared waste and waste sent to the central interim facility for conditioning/storage. The central facility should have the responsibility for monitoring, documentation and record keeping of all activities taking place there, including the record keeping of all the waste transferred to the facility. Special attention should be given to the record keeping and archiving system of the waste in the interim store. The information required in the records is the same as for class A countries.

TABLE XI. ADDITIONAL EQUIPMENT NEEDED FOR THE MANAGEMENT OF WASTE GENERATED IN CLASS B COUNTRIES

Management steps	**Equipment, tools, materials or facilities**	**Remarks**
Identification and characterization	Portable gamma spectrometer	It should be purchased or received by donation
Collection and segregation	Radiation bag monitor	For monitoring of low level solid waste from research and medicine
Conditioning by cementation	Motorized cement mixer	Justified if large number of disused sealed sources are generated

When commercial equipment are used in waste management, arrangement should be made to ensure proper maintenance of the equipment and availability of spare parts. If maintenance competence does not exist at the facility where the equipment is used, service contracts with the supplier should be signed.

6.6. MANAGEMENT OF WASTE IN CLASS C COUNTRIES

6.6.1. General approach

When a country wants to engage in operation of research reactors, the management of wastes would move to a domain that calls for technological efforts of some significance. This is mainly due to the presence of radionuclides (mainly fission products and some activation/corrosion products) of somewhat longer half-lives (say up to 30 years); this would mean efforts to isolate some of the nuclides from the human environment for a period of about 300 years. But the volume of waste from the operation of research reactors will be low enough for managing them with interim storage provisions for even a few decades, after necessary conditioning, untill a disposal option becomes available.

The technical requirements for waste management in a class C country differ from class A and B countries because there are larger quantities and different types of waste. The large quantities of waste and the increasing cost of waste disposal could justify the investment for waste volume reduction at a central waste management facility and for a transport system ensuring the safe transportation of unconditioned waste on public roads. The central waste management facility should develop acceptance criteria for the waste to be transported to and accepted by the central facility for processing. Some pretreatment like decay storage, size reduction or ion exchange should be done at the site where the waste is generated in order to minimize the volume of waste to be transported.

The diversity of radioactive waste generated in a nuclear research center or received by a central waste processing facility demands the introduction of an integrated system that can successfully process different categories of waste and produce a final waste package acceptable for long term storage or disposal.

6.6.2. Solid waste

Solid waste should be collected at the places of generation and segregated into waste for clearance, which is the largest part, and waste for interim storage. The waste for clearance can normally decay in the containers in which it was collected. For facilities where there are different waste streams it would be preferable to make arrangements for collection of all the waste with similar characteristics and decay requirements in one container for each type of waste, thus the storage volume and the use of containers would be more efficient. Therefore, it requires more precise monitoring and administrative procedures, especially record keeping, compared with similar activities in class A and B countries. The waste generated from the operation of a research reactor is much more complex regarding the radionuclide content than in the case of the use of radionuclides.

The waste generators should normally only pack the segregated unconditioned solid waste in standard transport containers and send it for processing and interim storage to the central waste management facility.

If the solid waste generation exceeds several cubic meters a year, installation of an in-drum compactor at the central waste management facility could be justified.

Decommissioning, especially of nuclear facilities, will generate significant quantities of solid and solidified waste during a relatively short period. In most cases the existing waste processing facilities will be capable of handling these decommissioning wastes, but there will be an additional need for decontamination, size reduction and handling of contaminated and activated equipment and building material. Even decommissioning of accelerators can give rise to contaminated and activated materials, which requires careful assessment before the operations commence.

At the waste storage facility, arrangements should be made for storage of waste packages with different characteristics separately due to different possible routes of such wastes for final disposal.

6.6.3. Liquid waste

Considering the larger quantities of liquid waste in class C countries, it is normally justified to establish some basic liquid waste treatment facility, which can process liquid waste generated at several waste generators. Such a basic facility may include ion exchange and chemical precipitation. Ion exchange resins used for absorption and/or adsorption should be directly cemented in standard waste containers together with chemical precipitation sludges. The facility should also consider the possibility of installing some other liquid waste treatment equipment if required.

A recommended conditioning method for the radioactive residues from the treatment of liquid waste is cementation. The conditioning equipment should be installed at the central waste management facility, but it might also be installed at one or more of the major waste generators.

The decision on the selection of treatment/conditioning techniques and their location should be made based on analysis of important local criteria, technological and non-technological factors, such as, socio-political factors, related physical infrastructure, availability of staff, transport requirements, availability of funds, waste volumes and characteristics, availability of storage capacities and/or disposal options, etc. The constraints imposed by national legislation, the investment and operation cost, the safety of the individual facilities as well as the national system as a whole, may have a very strong influence on selection and application of particular technologies for waste processing, storage and disposal.

Treatment of organic liquids can have more objectives than volume reduction and conditioning. It might include recycling/reuse of material after separating it from the radioactive waste, segregation of chemical toxic materials from radioactive waste or elimination of impurities, which can affect conditioning of liquid waste.

Both large incinerators and laboratory scale incinerators can — if already existing for other purposes — be used if an assessment demonstrates that all safety requirements are met.

Figure 5 provides an example of a decision making process in selection of waste management techniques and factors to be consider in the selection process.

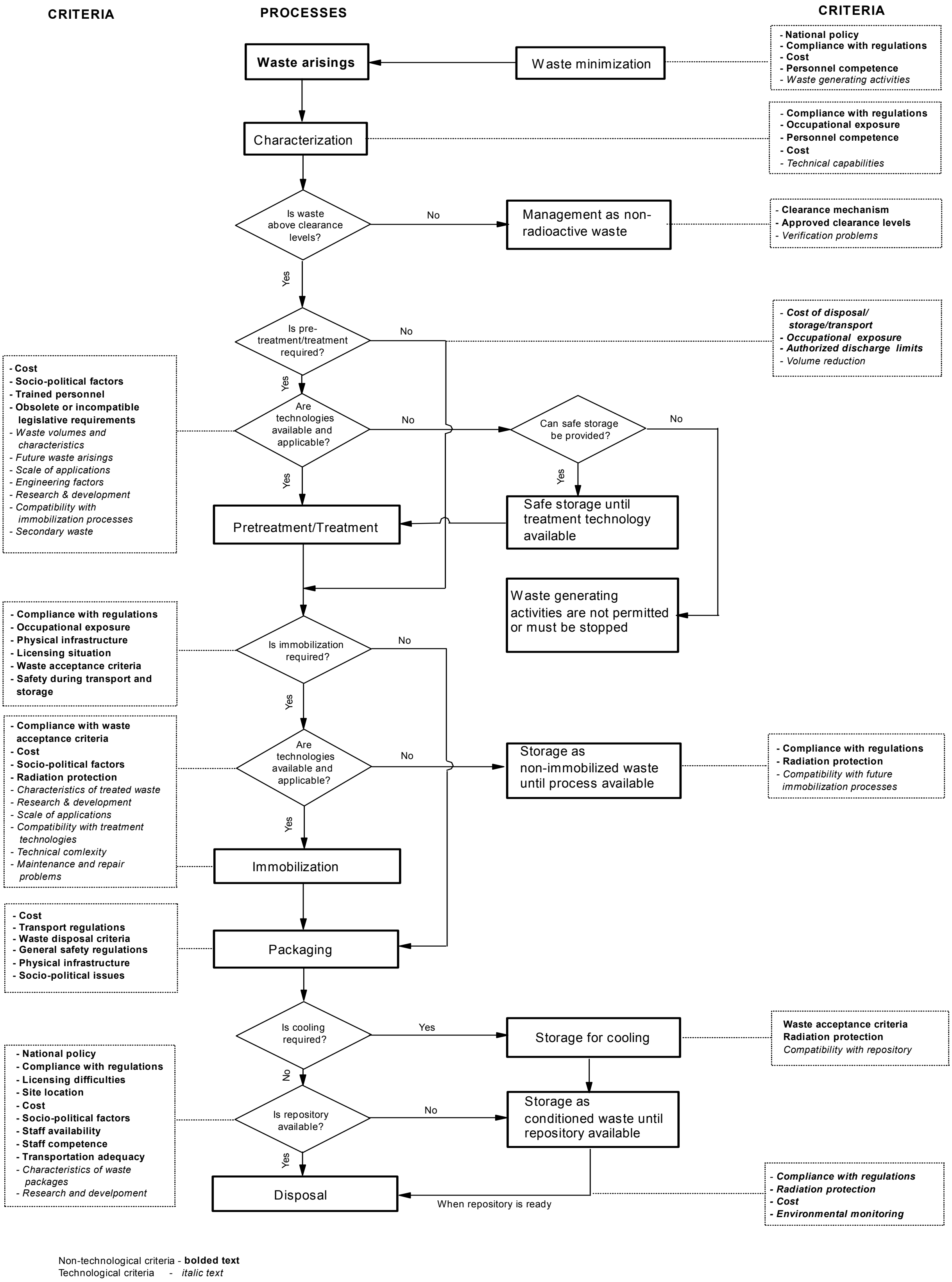

FIG. 5. Decision tree concerning the selection of a waste management technology.

6.6.4. Waste management equipment

In addition to the equipment recommended for class A and B countries, Class C countries would need the equipment listed in Table XII.

6.6.5. Quality assurance

A quality assurance programme for the management of radioactive waste should be established and implemented to provide the necessary confidence that adequate measures are taken to protect human health and the environment. This programme should cover, as a minimum, the design of waste processing and storage facilities, the quality of equipment and materials used, and the quality of resulting products. Emphasis should be given to the features, which are important to safety. Additionally, for conditioned waste appropriate steps should be taken to ensure that there is adequate quality control. The quality control must ensure that the waste packages are produced in accordance with the waste specifications and will meet the requirements for transport, interim storage an ultimately, disposal.

Development and maintenance of competence in operation of waste processing techniques is an important component of the quality assurance programme as well as an audit system to verify that the competence is adequate and that waste acceptance requirements are met.

TABLE XII. ADDITIONAL EQUIPMENT NEEDED FOR THE MANAGEMENT OF WASTE GENERATED IN CLASS C COUNTRIES

Management steps	**Equipment, tools, materials or facilities**	**Remarks**
Collection and segregation	• Plastic tanks for liquid waste • Stable containers for solid waste	• 0.5–3 m^3 • 200 L drums
Treatment of aqueous waste	• A small precipitation or ion exchange facility for liquid waste • A compactor for solid waste	• 2 m^3 capacity • In-drum compactor is appropriate
Conditioning	Simple in-drum mixer for sludge and/or spent ion exchange resins	
Storage	Separate building	The store should meet all safety and design requirements
Handling of waste packages	Fork-lift truck or other mechanical or hydraulic equipment	For transfer, lifting, stacking, dragging, etc. of heavy loads. Lifting capacity 1–2 t
Transport	• Small truck or trailer • Tank for transporting liquid waste	To be used with truck, trailer. Capacity 0.5–1 m^3
Laboratory investigation	• pH meter • Compressive strength machine	• For controlling chemical precipitation • For quality control of cemented products

7. CONCLUSIONS

The efficient and safe management of radioactive waste requires establishment of an appropriate waste management system in the country. This system may be very simple, depending on the amount and characteristics of waste produced, but it should be comprehensive enough to cover the most important components and parties involved.

These components include:

- legal basis for regulation of waste management practices;
- organization responsible for implementation of regulatory functions; and
- organization(s) responsible for waste management practices.

Management of radioactive waste should be considered as an integrated process from waste arising through collection, treatment and storage until final disposal in a way that ensures compatibility of all involved steps and the required level of safety. By considering sufficient level of comprehend and the integrated approach the general objective of radioactive waste management could most effectively be met.

Organizations implementing waste management practices in countries with limited waste generation may range from operators and organizations that use radioactive materials (and produce radioactive waste), to designated facilities which collect waste from small waste producers for centralized processing, storage and disposal. Selection of a centralized or decentralized strategy for waste processing basically depends on the scale of waste production, geographic distribution of corresponding activities, characteristics of waste produced, etc.

While a number of technology options are available in principle, the objective of safe and economic management of waste in a given situation will require selection of appropriate technical solutions taking into account waste characteristics, economy of scale and safety requirements. In countries with limited waste generation and limited financial resources waste generated can be safely managed with the help of rather simple, mature and non-expensive methods and technologies.

In general in class A countries the level of waste generation does not justify establishment of a special waste management organization outside organizations generating the waste. The authority in these countries should give the proper recognition of the waste generator as the waste management operator. In some cases it would be justified for the radiation protection authority, which entails basic waste management competence, to undertake the necessary waste management activities following the initial steps, which always should be done by the waste generators.

Waste management practices and technical requirements in class B countries could be the same as in class A countries, however, because of a larger number of waste generators, one of the waste generating facilities might be designated as a central waste processing and storage facility. It would lead to cost savings in providing all of the radiological measurement instrumentation and qualified staff at one selected facility only.

Procedures and technical requirements for waste management in a class C country differ from class A and B countries because of larger quantities and different types of waste. Large quantities of waste could justify the investment for centralized waste processing. Acceptance criteria for the waste to be transported to the central facility should be developed. The diversity of radioactive waste generated in class C countries demands the introduction of an integrated system that can successfully process different categories of waste and produce a final waste package acceptable for long term storage or disposal.

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