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Review of the factors affecting the selection and implementation of waste management technologies

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Waste Technology Section
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Wagramer Strasse 5
P.O. Box 100
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FOREWORD

The International Atomic energy Agency has published Safety Series and Technical Reports Series documents on basic requirements for radioactive waste management and state of the art reviews. Technical documents (TECDOCs) describing specific waste management technologies and procedures have also been published. Selection of the most suitable technology among many available options can be done on the basis of national preference or experience or following an optimization procedure. In any case, the selection mechanism requires clear criteria.

In order to help Member States streamline the process of selection of technologies most appropriate for the country, the IAEA decided to identify and critically review the technical and non-technical factors affecting the selection of waste management strategies and technologies, summarize and discuss the available options, and offer a systematic approach for considering these factors to design, install and operate optimal technologies for various waste streams.

A draft report was originally prepared by the IAEA Secretariat with the assistance of experts from both industrialized countries and countries with developing nuclear programmes. Its main conclusions were presented to and agreed by the International Radioactive Waste Technology Advisory Committee (WATAC) advising the IAEA on its waste technology programme. Six members of WATAC also assisted the Secretariat in the final review of the report.

The IAEA wishes to express its thanks to all who took part in the preparation of this technical report. The publication was finalized by V.S. Tsyplenkov of the Waste Technology Section of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Radioactive waste is generated in activities that involve the use of radioactive material. These activities may vary from the application of nuclear techniques in medicine, research and industry to production of electricity from nuclear energy. Radioactive waste may have potential negative impacts on human health and on the environment if managed improperly. The main objective of radioactive waste management is to manage the waste safely in order to protect human health and the environment from these potential negative impacts. The magnitude and type of the potential impacts resulting from radioactive waste will depend on physical, chemical and biological properties of the waste, in particular those related to radioactivity. The application of appropriate technologies at each step from waste generation to disposal will minimize or can prevent the potential negative impacts.

Waste management technology is a subject that has received considerable attention in the Member States in recognition of the important link between public acceptance of nuclear applications and the safe management of radioactive waste. This linkage must be maintained to ensure radiological safety for workers and the public and to avoid accidents and minimize exposure to radionuclides associated with the management of radioactive waste.

The optimal application of technologies related to waste minimization, treatment, conditioning, and storage or disposal has become a necessity because of the following factors:

- Radioactive waste can be disposed of only in facilities licensed to accept radioactive waste.
- Direct near surface disposal of radioactive waste into the ground (without appropriate treatment, immobilization and packaging) is not acceptable.
- Compared to the past, there is further restriction on the acceptable levels below which diluted effluents can be released to the environment.
- With steep increases in radioactive waste disposal costs during the past ten years, reducing the waste volume offers great economical advantages.
- The regulatory criteria for such steps in waste management as transportation, storage and disposal have recently become more restrictive.
- With increased societal concern regarding optimum use of land resources, and increased public opposition to the siting of radioactive waste facilities near their localities, the development of new facilities is an expensive, prolonged and difficult process.
- Recent advances in various technologies suited to radioactive waste management have made their application cost-effective and easier to implement.
- Optimum goals in terms of human health and safety and environmental protection can be achieved if waste management technologies are judiciously applied.

Much information is currently available about a multitude of waste management technologies and their technical alternative designs and about "emerging" technologies, which require development and/or validation. Not all of these processes are equally well developed, although each one may have its own merits, nor are they equally well adapted to all kinds of waste and situations. Selection among these technologies can be done on a national organizational preference or experience or following an optimization procedure. Because of the costs involved, the potential complexity of technical and environmental considerations, as well as the necessity to assure adequate performance, the selection mechanism will require clear criteria. Some criteria will be rather general and apply to almost all waste management systems. Others may apply to specific waste categories or to selected management steps.

In the past a multitude of technical reports has been issued by the IAEA that dealt with methods, technologies, and strategies for managing radioactive waste. However, the techniques described in these reports were not evaluated in terms of matching them with the development level of Member States. In reality, some recommended techniques have been widely applied, while others have never been implemented on a broad scale because, especially for the relatively small amounts of diverse waste generated from nuclear applications and research, there was little guidance on which available technologies are more appropriate.

1.2. CATEGORY SOURCE OF RADIOACTIVE WASTE

Since practices in different Member States range across a very large scale, to facilitate an internal understanding of issues, progress, and problems with more than 120 Member States, the IAEA has grouped their nuclear programmes into five classes. The grouping is in accordance with the extent of the use of radioactive materials. The Member State classification may change when their nuclear programme move from one group to another according to the criteria described below.

TABLE I. CATEGORY SOURCE OF RADIOACTIVE WASTE

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

SIA 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. SIA Member States are encouraged to return material with a higher activity ($\geq 10^9$ Bq) and longer lived ($T_{1/2} > 100$ d) to the supplier. The resulting waste consists of a few spent sealed sources, which may require specialized handling and packaging, and small amounts of low level solid or liquid waste.

MIA Member States use radioactive materials in a greater variety of applications, including the wide use of sealed and unsealed sources for medical, industrial, agricultural and research purposes. The radionuclides used may include both short-lived and long-lived ones. The waste generated comprises spent radioactive sources (including radium sources from brachytherapy, still used in some countries) and larger quantities of various medical and biological waste with significant concentrations of short-lived, but also some long-lived radionuclides.

RRA Member States practice all the activities of MIA countries, and in addition, have nuclear research reactors in operation for basic research and/or radionuclide production. The waste generated will, in addition to waste typical of SIA and MIA countries, include for example spent fuel elements, ion exchange resins, liquid waste from radionuclide production, and items with neutron activation products (e.g. ^{60}Co).

NPP Member States have all of the capabilities listed for RRA Member States, plus they have use of nuclear energy to generate power. In addition to waste typical for the first three groups, they will have the waste from operation of NPP (containing e.g. ^{137}Co, ^{90}Sr, other fission products, ^{60}Co, ^{54}Mn).

NFC Member States, besides nuclear power plants in operation, also have some nuclear fuel cycle facilities including those that may reprocess spent fuel. These states will also produce high-level and long lived alpha-bearing wastes.

1.3. GENERAL APPROACH TO THE SELECTION OF WASTE MANAGEMENT TECHNOLOGIES

When planning to commence the development of a national capability to produce or use radionuclides, to operate research reactors or to generate electricity by nuclear power plants, it is encouraged that the country begins by considering the full life cycle cost of such an action including the cost of the management of radioactive waste. The Member State must decide, before using nuclear energy or radionuclides, whether it has sufficient socio-economic benefits and adequate legal, institutional, financial, and technical resources to manage the full cycle impact of the proposed activity. Both non-technical and technical factors may affect the waste management decision making process. Often, non-technical factors have even more significance than technical factors. Moreover, the same non-technical issues may arise a number of times in the decision making process. In addition, there is a need to accommodate potential future waste streams when selecting a waste management option.

The main task of a waste management system is to safely handle, process, store and dispose of radioactive waste in compliance with national requirements and international obligations taking into account economical and socio-political factors involved. Because of the variety of processes, techniques and equipment available for different steps of a waste management scheme, for each step a proper technology has to be selected. The different technologies should be combined in an integrated system to optimize the radioactive waste management. In general, all factors listed in Table II and evaluated in Sections 2 and 3 should be considered while selecting a waste management technology.

No relative ranking of these general factors has been attempted here as it is likely that these factors could have varying degrees of impact depending on the specific, site/country related situation.

1.4. OBJECTIVE

The objective of this publication is to identify and critically review the factors affecting the selection of waste management strategies and technologies; summarize and discuss the options available, and offer a systematic approach for considering these factors to design, install and operate appropriate technologies for the waste streams generated.

1.5. SCOPE

The scope of this publication includes the management of radioactive waste from all orientations including low and intermediate level waste (LILW) arising from the production of radionuclides and their application in industry, agriculture, medicine, education and research; waste generated from research reactors, power reactors and from nuclear fuel cycle activities including reprocessing high level waste (HLW). Although waste from decommissioning is not specifically addressed, the management of this waste is not significantly different from other types of waste in the same category.

TABLE II. GENERAL CRITERIA FOR THE WASTE TECHNOLOGY SELECTION

Non-technical factors	**Technical factors**
Adequacy of a national waste management system	Waste characteristics
National policy, laws and international standards	Scale of technology application
Compliance with regulations	Maturity of the technology
Licensing situation	Robustness of the technology
Physical infrastructure	Field of technology application
Manpower and personnel competence	Treated product characteristics
Cost and resources	Anticipation of future needs
Socio-political conditions	Complexity and maintainability of facilities
Geographic and geologic conditions	Volume reduction
Opportunity for co-operation with other countries	Secondary waste and compatibility with existing processes
	State of research and development
	Safeguards and nuclear safety
	Potential for intrusion

Waste generated from the technologically enhanced concentration of Naturally Occurring Radioactive Materials (NORM) including uranium mining and milling waste are excluded from the scope of this report.

1.6. STRUCTURE OF THE REPORT

The report consists of six sections. Section 2 addresses the major non-technical factors affecting the selection and implementation of waste management technologies. Section 3 reviews the technical factors affecting the selection and implementation of waste management technologies. Section 4 describes two main strategies applied in radioactive waste management– centralized and non-centralized. Section 5 summarizes the general options and approaches to the technology selection for different waste management steps. Flow charts that illustrate decision making on specific waste streams are presented. Section 6 addresses some recent trends in waste management technologies.

2. NON-TECHNICAL FACTORS

2.1. ADEQUACY OF A NATIONAL WASTE MANAGEMENT SYSTEM

2.1.1. General requirements

The general requirements for a national radioactive waste management system are given in Ref. [1]. The extent to which a national programme develops the components of the system will depend on the individual national situation, including most importantly the amount and nature of the radioactive waste involved. The following elements are considered necessary parts of the programme for any Member State managing radioactive waste:

(a) identification of the parties involved in the different steps of radioactive waste management and their responsibilities;

(b) an appropriate set of radiological and environmental protection objectives;

(c) identification of existing and anticipated radioactive wastes, including their location, radionuclide content and other physical and chemical characteristics;

(d) control of radioactive waste generation;

(e) establishment of the appropriate mechanisms to assure that the responsibility of safe waste management is discharged;

(f) monitoring of any waste management facilities and practices to assure that safety objectives and legal requirements are met.

Some countries, particularly NPP and NFC countries, will need to establish more comprehensive national waste management systems. To provide the necessary degree of control and safety of relatively large quantities of waste and diverse waste types, these countries should assure that the following elements are in place for their national programmes:

(a) a national policy;

(b) an independent regulatory capability and associated legal framework;

(c) identification of available methods and facilities to process, store and dispose of radioactive waste on an appropriate time-scale;

(d) appropriately accounting for the interdependencies among all steps in radioactive waste generation and management;

(e) research and development to support the operational and regulatory needs; and

(f) the funding structure and the allocation of resources that are essential for radioactive waste management, including decommissioning and, where appropriate, disposal.

If some components of the national waste management system are missing or do not comply with the internationally endorsed requirements or recommendations, the effectiveness of any waste management technology employed may be compromised.

2.1.2. Administrative and organizational structures

The process for selecting waste management technologies must be consistent with the accountability and authority established for waste management. This process will depend strongly on the particular organizational structure.

Management of radioactive waste should start when work with radionuclides is considered and, ideally, plans should be made in advance for waste handling, processing, storage, and disposal. The initial steps of waste management operations must, for obvious reasons, be done by the waste generator at the place where the waste is generated. For that purpose, a person or persons must be allocated to the task of waste management within the organization where radioactive material is used.

It is vital that authority and accountability for decisions on waste management be clearly defined. The complexity and size of the organizational structure will depend on the quantity and diversity of the waste involved. In cases where the quantities are low, such as for some SIA and MIA countries, responsibility and authority may rest with a few individuals. On the opposite end of the spectrum, the organizational structure may include a central waste management organization and an independent Regulatory Body as well as multiple waste generators.

2.1.3. Generation of radioactive waste

A very important issue in the selection of a waste processing system is a critical review of the waste generation practices. It is recognized that great savings in the waste management cost can be achieved by screening the operational practice and modifying it in a view of careful waste minimization. At the waste generation, site appropriate segregation of the waste in view of their successive treatment can contribute significantly to waste minimization.

2.1.4. Responsibility for safety

Upper management are responsible for the safety of workers under their authority and the safety of the general public. Thus they have a responsibility to assure that the selected technology will achieve these objectives.

It is vital that upper management establish appropriate training practices and foster and maintain an appropriate attitude toward safety within their organization. The key aspect of the safety programme is to ensure that personnel have both the capability and the motivation to achieve safety objectives. The success of the safety programme within the organization will depend in large degree on the appropriateness of the waste management technology being employed.

2.1.5. Quality assurance

Quality assurance (QA) is a process that is intended to provide the necessary confidence that adequate measures are being taken to ensure that a facility or process is built and operated in a way that fulfills its intended function. Quality assurance requirements for radioactive waste management facilities have their origin in similar requirements developed for other complex nuclear facilities built and operated by NPP and NFC countries. These countries realized that complex human activities, such as radioactive waste management, may not achieve their objectives because of inadequate procedure specification and verification of required actions. This observation applies to both construction and operation of facilities and processes. Application of QA measures to all waste management steps, including design, construction, and operation is intended to overcome this difficulty.

In situations where waste management activities are relatively simple, as may be the case in some SIA and MIA countries, QA measures can be relatively simple as well. The important requirement is that, those responsible should have a means of independent cross-checking that required elements of the operations are being correctly executed and that safety objectives are being achieved. This would entail adequate measurement, inspection and record-keeping. Orders for equipment and services should specify appropriate QA standards for suppliers, and any performance measures defined for waste forms, equipment, and operations should be checked.

In more complex cases, and particularly for NPP and NFC countries, a formal quality assurance programme should be established. This is normally accomplished by first establishing a standard or a set of standards, which specify authorities, responsibilities, documentation, and control measures to be employed in waste management Such standards are typically sanctioned at the national or international level. Whether or not a formal standard is applied, the responsibilities and authority of personnel and organizations involved in implementing a QA programme must be clearly delineated.

2.1.6. Documentation and records

Responsible authorities, waste generators and operators of radioactive waste management facilities should establish and maintain documentation and records consistent with legal and QA requirements and their own needs. These records should be kept in a condition that will enable them to be consulted and understood later by people different from, and possibly without reference to, those who generated the records. The basic requirements of record retention include, but are not limited to:

- designation of the records as permanent or temporary;
- storage of temporary records for a specified length of time;
- storage of permanent records in perpetuity;
- designation of the method of record storage.

One example that illustrates the usefulness of this process could occur in relation to waste disposal or facility decommissioning. The Regulatory Body may choose to take the responsibility for the long-term retention of the above mentioned records. In any case, the disposition of operator records should be clearly understood by all parties involved, and established in writing during the licensing process. The record keeping requirements should be commensurate with the level of Member States' commitment to the use of radioactive materials.

2.1.7. Technical capability

Appropriate technical capability to perform the assigned task must be established and maintained at every site where radioactive waste arises and/or is managed. This capability includes the facility itself, appropriate equipment, and technical competence of the operators. Acquisition and operation of facilities and equipment should be commensurate with the available technical capability, to facilitate effective and safe operation.

The technical management 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. Each waste generator needs technical capability to collect, characterize and segregate the radioactive waste as well as to store it for decay. The generator needs also the verification capability to ensure that radioactive waste to be cleared 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, the Regulatory Body, or through an international peer review.

In cases where large amounts and diverse wastes are managed, and particularly for NPP and NFC countries, substantial technical capability must be established and maintained. The discussion in the remainder of the section applies to such cases.

When a central waste operating organization exists, the largest technical capability needs to be established there. Its personnel should have basic knowledge and experience in management of radioactive waste, and should have equipment and facilities 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 QA programme especially related to management of long-lived radioactive waste.

Because of the complexities of generation and distribution of radioactive materials in nuclear reactors and radioactive processing facilities in RRA, NPP, and NFC countries, it is essential that some of those responsible for waste management have a 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 could have long-term impact. It can also help to avoid the unnecessary production of such radionuclides through design and operational improvements.

The Regulatory Body does not usually have the responsibility to act as operator of a waste management facility, however the regulators should possess necessary knowledge and experience to administer laws and regulations and provide clear guidance and direction to the operators of waste management facilities.

An adequately trained workforce shall be provided for each step of waste management in order to ensure the objectives of efficient and safe waste management operations are met. Appropriate staff training programmes should be established to secure the necessary competence of staff, to foster the necessary dedication to quality and safety, and to keep the staff up to date with changes in relevant technology and regulations. Training programmes may be initiated and/or supplemented by Member States through bilateral agreements with other countries, through international organizations or by vendors of facilities purchased for installation and use. The further maintenance of an educated and adequately trained workforce to support waste management is essential to continuity of safe operations.

The waste generator may not need to be aware of details of how the waste will subsequently be managed, if the job of processing the waste 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 or classify the waste before collection.

The most important task of waste management lies with the waste management facility operator. These staff process, transport, store and eventually dispose of the waste. Training at all skill levels is required. Hence, they should have essential knowledge and skill related to their task and periodic retraining to ensure a comprehensive understanding of and compliance with safety requirements. Training of these personnel needs to emphasize hands-on operation of equipment and work with real waste.

2.1.8. Emergency planning

Where radioactive waste management activities have the potential to adversely affect human health and the environment through an accident, Member States need to provide for emergency planning and make such provisions as might be necessary to respond to the accident.

Often, existing emergency response capabilities in the country are reasonably well suited to respond at a level appropriate to the need (i.e. fire protection, traffic control, ambulance and medical services). In this case, it is the responsibility of the operator and the Regulatory Body to inform the local state authorities and emergency response personnel of this new operation in their area. They are then aware of the new installation, and can assess the equipment and services they provide against this new hazard. The Regulatory Body may consider providing additional funding to local emergency response organizations in order to respond to any additional needs that may arise.

2.1.9. Institutional control

Management of radioactive waste should, to the extent possible, not rely on long-term arrangements for active institutional control after facility closure. However, institutional control may be required for an appropriate duration after closure of a facility, especially in the case of a near surface disposal facility, to:

- prevent intrusion;
- prevent removal of, or interference with, the radioactive waste;
- monitor the performance of the repository against the design criteria; and
- perform any necessary remedial actions.

The control can be active (e.g. continuous monitoring, periodic inspection, or maintenance), or passive (e.g. installation of permanent markers or establishment of land use restrictions). The maximum duration of the control that the operator can take credit for in the safety assessment should be determined by the Regulatory Body.

2.2. NATIONAL POLICY, LAWS AND INTERNATIONAL STANDARDS

2.2.1. National policy and laws

National policy, laws and government decisions have a significant influence on waste management.

National policy style definitely determines waste policy style. The change in national policy may lead to the change in waste policy. The examples of the waste policy are the following:

- Government will require the establishment of waste management integrated systems.
- Government will subsidize prevention and recycling of waste.
- Prevention, characterization, waste segregation, and treatment will be pursued at the facility level, conditioning and interim storage on a regional scale, and disposal on a national scale.

Certain waste management technologies may have an advantage over others, but are not permitted by the law of a country. This may delete such options from further consideration. For instance, clearance levels for release of waste from regulatory control are not established in the country, or a national law prohibits the export of radioactive waste outside national borders, even though a neighboring country is willing to accept the waste for treatment or conditioning. At the international level, Member States which are signatories to international conventions may need to comply with their requirements, which may restrict certain waste management practices. In this respect, a relevant Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management [2] should be mentioned.

2.2.2. International standards and guidance

Internationally accepted standards and guidelines aimed at ensuring the protection of human health and the environment from the hazards associated with ionizing radiation in general, have been developed, such as the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [3], or the Recommendations of the International Commission of Radiation Protection (ICRP) [4, 5]. These documents are based on a substantial body of scientific knowledge and a wealth of experience in dealing with radioactive materials. The IAEA has used these documents as the basis for the development of safety principles and requirements that underlie the safe management of radioactive waste. The internationally accepted fundamental principles of radioactive waste management [6] fall into the following general subject areas: protection of human health; protection of the environment; protection beyond national borders; responsibility to future generations; and implementation procedures. These principles are given below.

Principle 1: Protection of human health
Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.

Principle 2: Protection of the environment
Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

Principle 3: Protection beyond national borders
Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.

Principle 4: Protection of future generations
Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

Principle 5: Burdens on future generations
Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.

Principle 6: National legal framework
Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.

Principle 7: Control of radioactive waste generation
Generation of radioactive waste shall be kept to the minimum practicable.

Principle 8: Radioactive waste generation and management interdependencies
Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.

Principle 9: Safety of facilities
The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

Guidance documents issued on the international level may also affect the selection of the technology. For instance, the IAEA Code of Practice on Transboundary Movement of Radioactive Materials [7] may exclude other countries from managing radioactive waste of foreign origin if the recipient country does not comply with specific requirements of this document.

2.3. COMPLIANCE WITH REGULATIONS

Legal requirements have a significant influence on the selection of waste management technologies. In most countries, the management of radioactive waste must be conducted within an extensive framework of regulations, rules and norms issued by national and/or state governments or regulatory authorities. The national regulations often relate to nuclear safety, dose limitations of radiation exposure, transport and disposal requirements, whereas specifications for handling, treatment, conditioning and storage are imposed by state nuclear competent authorities or national waste management organizations. It is necessary to integrate the requirements imposed by different regulatory authorities and assure compliance with them during design, construction and operation of waste management facilities.

2.3.1. Safety and environmental protection

One of the basic waste management principles [6] requires that the safety of facilities for radioactive waste management shall be appropriately assured during their lifetime. When waste management practices are relatively simple and volumes and diversity of waste are low, such as may be the case in some SIA and MIA countries, extensive, costly, and time consuming practices are seldom required. When purchasing facilities or equipment from other Member States, these countries may negotiate the *safety and environmental impact assessment* as part of the total cost of the technology. However, when the waste management practices are sufficiently complex, the following considerations apply.

Siting, design, construction, operation and decommissioning of a waste management facility should be carried out giving safety matters priority in such a way that it seeks to prevent accidents and to limit consequences if accidents should occur. Public issues should be addressed throughout these steps. Site selection should take into account relevant features which might affect the safety of the installation or which might be affected by the installation. Design, construction and operation should provide and maintain, where applicable, several levels of protection to limit possible radiological impacts.

Consistent with national regulatory requirements, a safety assessment of the facility and its operation, and an environmental impact assessment, should be prepared for:

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

Such assessments should demonstrate compliance with national regulatory requirements and provide a basis for the Regulatory Body to review and approve the facilities or practices. They should take account of the complexity of the respective facility or practice. The complexity of these analyses should be commensurate with the risk posed by the facility or practice. These analyses generally place more onerous demands on NFC Member States than those on SIA and MIA countries.

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 mitigative measures necessary to protect human health and the environment. These measures, which ensure that there are no significant adverse effects on the environment, must be considered as an integral part of the waste management project. The technology chosen should ensure that mitigative measures are practical and effective. Section 3 discusses some technical factors pertaining to mitigative measures.

2.3.2. Non-radiological requirements

The technology employed in a waste management system, inclusive of specifically designed mitigative measures, must assure protection of the environment from all potentially significant adverse environmental effects. National and international standards for protection of the environment must be adhered to in considering the direct effects of the changes in the environment caused by the project as well as the effects that may result from noise, heat, and emissions of solid, gaseous, and liquid chemicals. The project will have to assure that environmental objectives are achieved at all stages of the project. These objectives include protection of air quality, protection of surface and subsurface water, and protection of ecological resources. The environment will normally be protected by national legislation and must be considered in implementing a waste management technology.

2.3.3. Radiation protection requirements

2.3.3.1. System of radiation protection

The selection of waste management technologies is strongly influenced by safety requirements that ensure that the workers, critical populations, and the surrounding environment are protected from adverse effects of radiation. The system of radiation protection [3] provides a widely accepted and coherent basis for protection of the workers in nuclear installations that generate and manage radioactive waste, and for protection of the public from both radioactive effluent releases and disposal of solid radioactive waste. It is based on *justification* of practices that lead to potential exposure, *optimization* of the practices and *dose limitation*.

It should be noted that no special justification is needed for waste management activities, just the activities resulted in generation of radioactive waste must be justified. However, optimization of the waste management option chosen should be considered thoroughly as well as dose limitation. The system of dose limitation requires that:

(a) all exposure shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account, and

(b) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the ICRP.

2.3.3.2. Occupational exposure

Occupational exposure is related to all steps of radioactive waste management in such a way that:

- Segregation of waste at the source and sampling may facilitate later treatment or make it more efficient; simultaneously, it implies exposure of operators. Even fully automatic segregation requires maintenance of (contaminated) mechanical and other devices.
- Characterization of untreated and treated waste through sampling and laboratory tests implies additional exposure.

- Treatment and conditioning of waste may require human intervention during treatment, maintenance of the treatment equipment, sampling, etc.
- Interim storage and the operational phase of disposal also imply some form of exposure of operators.

Occupational exposure in any case shall not exceed the authorized levels and can be restricted through remote handling, selection of treatment equipment which require less human intervention and less maintenance, adequate choice of characterization methods, etc. Optimization of management systems with regard to operator's exposure may be a major cost factor, essentially for highly active or α-bearing waste.

Therefore, the issue of occupational exposure is to be considered in all decisions concerning the selection of a waste management technology. Furthermore, it may be a substantial part of the overall exposure of the population, since operators belong to the population, and this fact implies cost/benefit evaluations where cost and benefit cover the monetary value as well as the exposure of population and of the operators, and vice versa.

2.3.4. 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 [8]. If it can be shown that any radiological hazards resulting from the release are negligible (specifically that they meet the criteria for clearance), the materials should be cleared from regulatory control. *Clearance* can apply both to materials that are being discarded as waste and to materials intended for further use or recycling. Consequently, cleared waste may be treated as normal refuse or effluent, and materials cleared for re-use or recycling may be sold to any other party and used for any purpose.

Regulatory authorities may decide that a dilute and disperse disposal method is appropriate in some circumstances, even if the retained material does not qualify for clearance. In this case radioactive waste in liquid or gaseous form may be released to the environment through *authorized discharge*. While control of the discharged material is lost, the process of release to the environment is kept under regulatory control. Control is carried out at the point of discharge and surveillance is performed in the environment.

Regulatory control of materials intended for re-use or recycling, but which do not meet the criteria for clearance, may be relinquished when such use is authorized by the Regulatory Body and when the *authorized use* has been verified.

When it is unacceptable that regulatory control be relinquished, radioactive materials must be dealt with by *authorized disposal*, in the case of waste, or *authorized transfer*, in the case that the materials will be re-used or recycled within another regulated practice. The relationships between clearance, authorized discharge, authorized use and retention of regulatory control are illustrated in Fig. 1. The upper part of the diagram represents a region where materials may be cleared because exposures are estimated to be trivial and not worth regulating. The lower part of the diagram represents the region where regulatory control of materials must be retained because the risks arising from the lack of control are regarded as unacceptable. The central part of the diagram represents a region where a regulated practice may be authorized to release certain materials under specified conditions. Figure 2 illustrates the decision-making process.

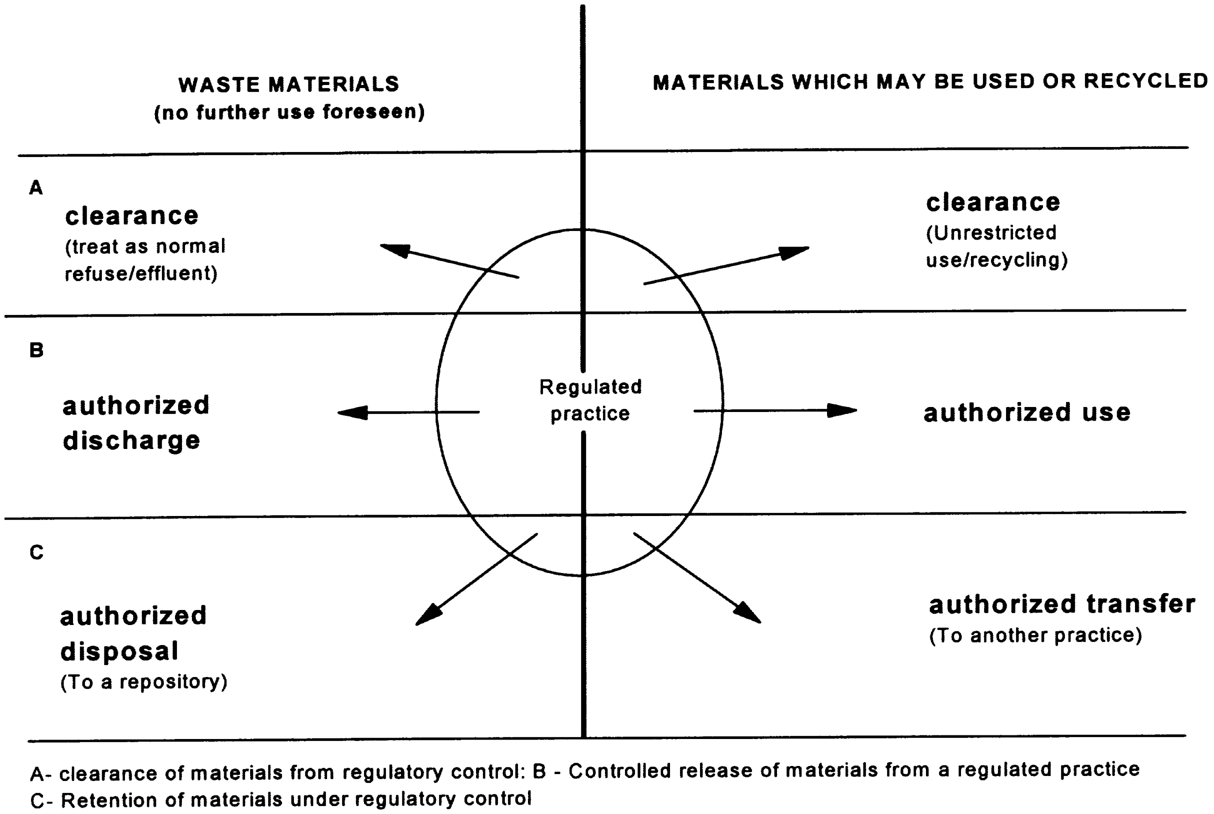

FIG. 1. Regulatory processes for dealing with relinquishing or transfer of regulatory responsibilities for radioactive materials.

2.3.4.1. Clearance levels

Clearance seems to be an efficient and safe mechanism for volume reduction of radioactive waste, however, at present clearance of waste either does not exist in many Member States or is currently handled in some Member States using ad hoc criteria based on existing legislation. In making a case by case authorization, the regulatory authority assesses the type and quantity of materials to be cleared, 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 maximum total activity or concentrations levels are set by the regulatory authorities.

Generic clearance levels are calculated on the basis that the dose criteria for clearance are met for all relevant scenarios of exposure from the material. The dose criteria for clearance are the same as the dose criteria for exemption. It should be stressed that if clearance levels are not established on a national level permanently or cannot be introduced on ad hoc basis, there is no legal basis for release of very low level radioactive waste from regulatory control.

2.3.4.2. Authorized discharge limits

As result of waste treatment most of the activity is concentrated in the lower volume while larger volumes of slightly contaminated liquid and gaseous effluents could be released under the limits authorized by national regulatory authorities. Any uncontrolled releases of radioactive liquid and gaseous waste effluents from nuclear facilities are not allowed in most Member States by national regulations. However, it must be understood that there is the potential for the uncontrolled releases of liquids and gases with the creation of extensive contamination and therefore every effort must be made to avoid leaks, spills, or other unplanned releases.

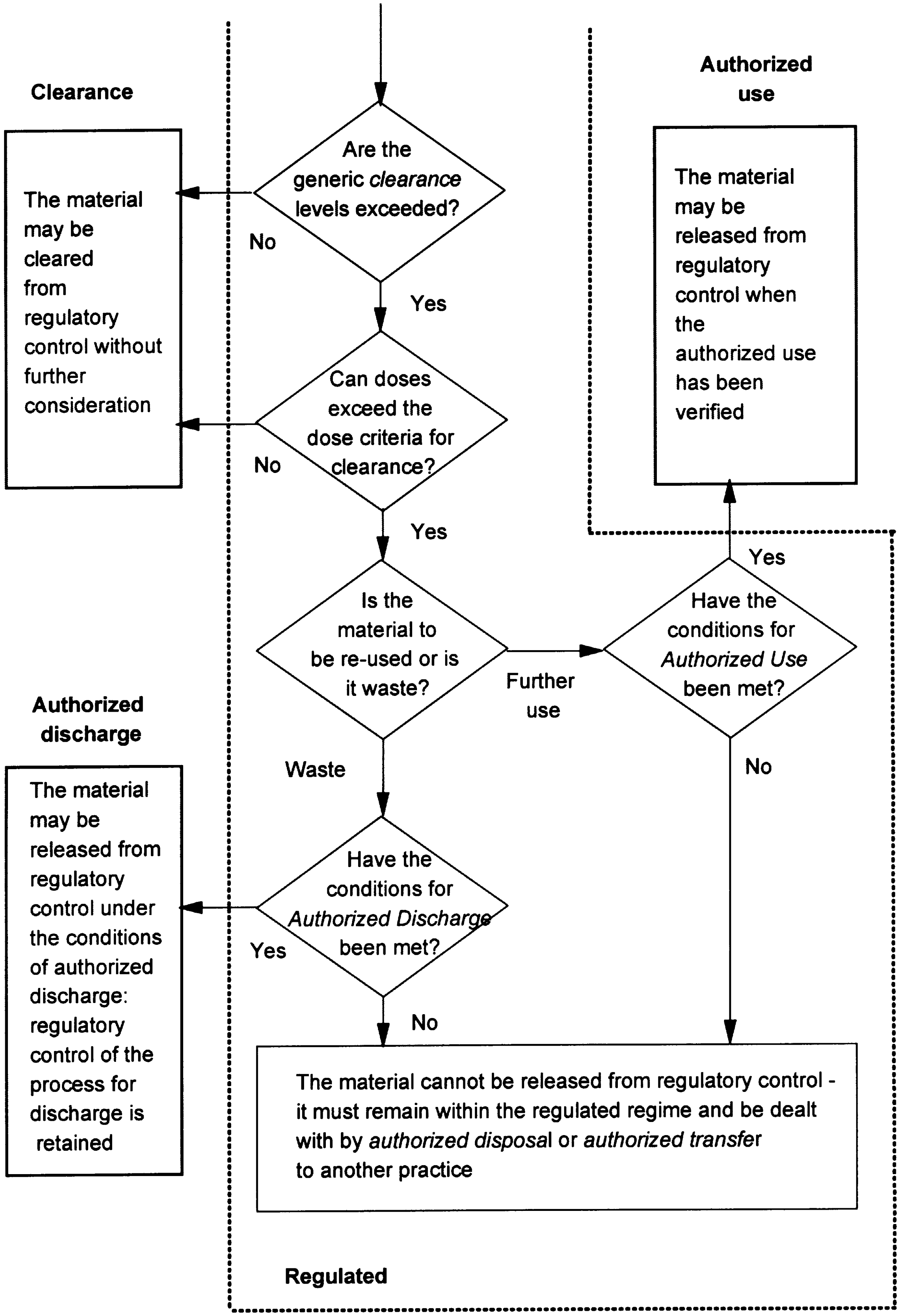

FIG. 2. Decision chart for release of radioactive materials from regulatory control.

Control of discharges of radioactive effluents is normally exercised through the granting of permits, licences, or authorizations by a Regulatory Body to the operator of a nuclear facility. Such licences, 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 that the operator must comply with. In granting an authorization the Regulatory Body considers the capability of the operator to comply with its conditions which might include record keeping, arrangements for training, and environmental monitoring.

Consideration should also be given to non-radiological hazardous contents 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 disposal of the waste.

2.3.4.3. Waste acceptance criteria

All radioactive waste which cannot be discharged under authorized limits or cannot be deregulated by clearance, must be disposed of in a licensed facility (repository) specially designed for this purpose. Usually only solid or solidified waste forming a "waste package" is permitted to be disposed of in a repository. The protection measures are provided by applying a multiple barrier approach to the disposal system taking into account interdependencies among various waste management steps. Multiple barriers are aimed at sufficient isolation of the waste from the environment and limitation of possible releases of radioactive materials, ensuring that failures or combinations of failures that might lead to significant radiological consequences are of very low likelihood. Only waste packages which comply with so called "waste acceptance criteria" (WAC) are accepted for disposal.

Waste acceptance criteria constitute an agreement among the waste generator, transport organization, and waste disposal facility operator regarding the minimum characteristics of each waste package (comprising a waste form and any container(s) and internal barriers, e.g. absorbing materials, liners). Formally WAC are considered as requirements and they are imposed on the waste generator by the Regulatory Body or by the operator of the disposal facility on behalf of the Regulatory Body.

A case also exists where waste packages are being 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 to be produced, processed, or accepted from another organization. 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.

2.3.5. Transport regulations

If a waste treatment/conditioning facility is located away from the nuclear facilities generating the waste, it will be transported to this facility according to the national transport regulations. Moreover, only in very rear cases disposal facilities are collocated with waste conditioning facilities. It means that the waste packages produced for eventual disposal must also be transported to the repository. Transport regulations are in many countries based upon IAEA Safety Standards Series No. ST-1 [9]. The IAEA regulations specify the requirements for packaging and labeling, define shipping categories of radioactive materials according to their radioactivity content and determine acceptable radiation dose levels. The waste packages prepared for disposal and to be transported to the repository shall comply with the transport regulations or additional packaging shall be provided.

2.4. PHYSICAL INFRASTRUCTURE

The extent at 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 transportation system and local factories which may produce components (e.g. waste containers) needed for the waste management facilities are some examples of infrastructure constraints which can affect the process of selecting optimum waste management technologies. For example, in some Member States, a combination of road, rail, and water borne transportation for each waste package must be provided to the central waste operating facility.

2.5. MANPOWER AND PERSONNEL COMPETENCE

The availability of manpower with a certain level of personnel competence for operation, maintenance and for secondary interventions, such as facility and product surveillance, are usually important factors. The level of the competence will influence the selection of waste management technologies. Essentially in small facilities operating for limited waste generating programmes, the availability of qualified manpower may be a difficult criterion in the selection of a treatment process.

The requirements for technical capability of personnel are discussed in Section 2.1.7.

The personnel availability and training opportunities in waste management are limited in Member States with developing nuclear programmes due to the lack of experience and proper education. From another perspective, trained personnel are often difficult to retain in the Member State for several reasons. First, key personnel are often attracted by better offers from other waste management agencies external to the country. Second, waste management activities in some Member States are relatively small. Trained personnel are often multidisciplinary, and are moved to the job where they are most needed.

2.6. COSTS AND RESOURCES

A basic non-technical factor, which may greatly affect the selection of a waste management technology, lies in the financial resources of the Member State and its willingness to commit them to an established and progressive waste management programme. The lack of adequate funding could result in non-compliance with regulations and safety requirements, or inability to provide most basic services. A Member State should not embark on a programme leading to use of radioactive materials including nuclear power generation until the financial impact of that decision is fully understood. The cost, eventually borne by its citizens, may be high.

The cost of different technologies can vary greatly. Consequently, the choice of technology may be greatly influenced by economic considerations. In making such choices it is imperative that all requirements for safety and environmental protection be met and that the risk of the waste management practices be as low as reasonably achievable, taking social and economic factors into account.

In an effort to take account of cost considerations effectively, the parameter of "total life cycle cost" was introduced. It covers:

- All costs for investment, depreciation, operation, decommissioning, and manpower.
- Parallel costs for the handling of secondary waste, for surveillance and monitoring.
- Costs for additional research and development, demonstration and/or adaptation.

Process life cycle costs are to be integrated into systems life cycle costs. Studies performed by US DOE [10, 11] allow the evaluation of life cycle costs for a large number of current and innovative processes for treatment of low level waste. The processes evaluated belong to the category of high temperature processes (e.g. incineration, vitrification, molten metal treatment) as well as to the category of low temperature processes.

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

A similar observation can be made for other essential features such as exposure of operators. More efficient treatment processes can result in higher volume reduction but simultaneously may increase the exposure of operating personnel.

The structure and mechanism of funding may vary from one country to another. The government that promotes the use of nuclear energy/applications normally supports related R&D and regulatory control of the waste. The waste generator, to a certain extent, may be charged a certain portion of the cost of management by the central waste management operator.

Countries which rely on the import of equipment and materials for processing (e.g. radiation monitors, gamma-spectrometers, chemicals, steel drums) may be affected by import controls and currency depreciation.

2.7. SOCIO-POLITICAL CONDITIONS

The introduction of a large scale waste management technology within a country generally requires public participation and acceptance. The NIMBY (Not In My Backyard) and BANANA (Build Absolutely Nothing nuclear Anywhere Near Anything) syndromes have affected the citizens of many Members States, and the situation is more critical for a country with a scarce land area or land with a high economic value. A political decision may overrule the technical feasibility of an area designated for the development of a waste management facility.

Opposing organizations have been able to raise concerns with politicians and the public that have had significant effect on the course of waste management projects. Member States should consider all stakeholders in planning such projects and should consider making consultation with the public during the technology selection process.

Although the negative perception of things nuclear is often highlighted, the positive economic and safety benefits of a waste management technology on a community should not be overlooked. The base of a waste management technology in a community brings with it an influx of money to the community. The average education of the residents increases, and with that comes the demand for better educational opportunities for all the children in the community. Overall, the standard of living increases, and the citizens of the community accept and appreciate the benefits of waste management technology. It should be emphasized that these benefits are not compensating for a compromise on safety. Safety of the facility is assured as a fundamental principle.

An effective public outreach programme will be a useful effort in allaying fears among members of the public. The public needs to be informed to avoid partial judgment on the analysis of technical adequacy in managing radioactive waste. A lack of emphasis on this area can result in a negative implication on public perception, especially when organized opposition to the siting or development of nuclear facilities develops.

Demonstrated commitment by the governmental authority is also essential to overcome public resistance. Respect and appreciation for the problems of indigenous peoples, and those organizations fearful of nuclear development for whatever reason, should be a part of any development programme. In all cases, the benefits of development must be shown to outweigh the negative impacts perceived by special interest groups. If possible, they should be brought into the process of site and technology selection When they are part of the process, it is more difficult to oppose decisions reached by groups in a democratic way. Likewise, the benefits of this technology should not be overlooked, and communities affected by decisions regarding nuclear technology should be made aware of the economic and social benefits that such a technology will bring to them.

2.8. GEOGRAPHIC AND GEOLOGICAL CONDITIONS

The geography of the country can have a major influence on the suitability and practicality of waste management technologies. For example, various technologies may have greater land or water requirements than the people of the country can or wish to devote to a waste management facility. In such a case, part of the waste management practice may be contracted to another country or the waste management system may be designed to accommodate the particular constraints.

A particularly strong influence of geography impinges on the potential for disposal of spent fuel or high level reprocessing waste. If a country is considering the final disposal of this material, the following realities must be considered:

(a) The only technology that has received a large degree of technical acceptability for final disposal is deep geological disposal. Other technology, such as transmutation, may, with future development, facilitate waste management, but would not eliminate the need for geological disposal.

(b) Geological disposal has restrictive requirements on the geological and environment conditions at a potential site.

(c) Deep seabed disposal is not acceptable internationally.

A country may thus find itself severely constrained in its ability to finally disposed spent fuel or HLW. The ultimate criterion will be that a safety case can be made for the particular geological situation that is acceptable on a national and international basis.

2.9. OPPORTUNITY FOR CO-OPERATION WITH OTHER COUNTRIES

The availability of resources in other countries (especially in neighboring countries) should always be considered when selecting a waste management technology. It may be possible to send waste to another country e.g. for treatment and immobilization. It may be possible to hire equipment from neighboring countries to facilitate, for example, supercompaction. In this connection, the existence of bilateral or regional co-operation projects can be very important to save money and lower potential hazards to the population. Regional waste processing centres, 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.

Other forms of international co-operation to achieve waste management goals includes exchange of staff, and agreements to accept certain types of waste (i.e. spent fuel from research reactors) after it can no longer be used for its intended purpose. 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. NPP and NFC countries in particular have an interest in assuring that accidents involving waste dispersal in Member States do not occur, as their assistance will almost certainly be required to clean up the contamination. These countries are well aware that the waste volume from such incidents is many times the original amount intended for disposal, and that the cleanup process may involve great time, risk and expenses.

The potential of international co-operation or some iteration of it has been underutilized by most Member States for non-technical reasons. The Member States with developing nuclear programmes have the most to gain from regional facilities, which link neighboring countries in waste management activities, thereby melding their futures in other areas as well.

3. TECHNICAL FACTORS

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

3.1. WASTE CHARACTERISTICS

The characteristics of radioactive waste have a major technical influence on the selection of waste management technologies. Indeed failure to understand the characteristics of the waste before selecting the technologies will increase the risk of the process not operating successfully. Waste can be categorized into seven generic groups (it must be mentioned that these groupings may not be mutually exclusive):

- Solid waste (includes HLW and LILW).
- Spent fuel.
- Spent sealed sources.
- Bio-hazardous waste.
- Aqueous liquid waste.
- Organic liquid waste (immiscible with water).
- Gaseous waste (including airborne effluents).

Each waste group may consist of material contaminated by radionuclides which are differentiated by activity (α emitters, β/γ emitters, fissile materials), half-life, and by their different physical, chemical and biological properties.

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

- physical state (solid, liquid or gas);
- quantity (volume and mass);

- dimensions of waste items;
- density (as received and theoretical density);
- morphology (powder, sludge, crystalline, colloids, aerosols);
- water content;
- level of segregation (i.e. one discrete waste type or a mixture);
- colligative properties of liquids.

Chemical properties also play an important role in the selection of technologies to condition or treat waste. Consideration of the following will aid the identification of appropriate technologies:

- chemical composition (including chelating agents);
- organic content;
- acid/alkalinity;
- chemical stability (corrosion);
- toxicity;
- putrescability (biodegradation);

Having embarked on technology selection it may be necessary to identify and measure some more detailed physico-chemical properties, for example:

- viscosity;
- surface tension;
- pour characteristics (powders);
- compactability;
- oxygen demand;
- surface properties;
- redox potential.

Biological properties will play a part in technology selection for waste treatment technologies. The presence of any infectious or bio-toxic hazards may require specific process steps. Features that should be defined are:

- putrescability;
- biodegradation;
- infection.

In addition to physico-chemical and biological characteristics the wastes are also defined by the *radiological properties* of their radioactive components. Strictly speaking radiological properties are part of physical properties of radionuclides. These include:

- half-life;
- type and energy of emission, (α, β, γ-rays, neutrons, etc.);
- concentration;
- decay chain.

These factors will in their turn determine the heat generating properties, shielding requirements, containment needs, criticality constraints and radiation resistance.

Much of the waste held by Member States are “historical waste” generated some years ago and may be inadequately or inappropriately stored. In these cases the condition (degree of degradation of the waste or its packaging) is influential in the choice of technology(ies). A national waste management organization is usually empowered after waste already exists in the country. In practice, radioactive waste management becomes a necessity in Member States because materials are introduced into the country before a Regulatory Body exists for legitimate purposes to control their distribution, use and disposal. At the same time, the challenge to the national organization is to select techniques for the past waste, which cannot be avoided, and the future waste, which holds many more uncertainties As a result, the national authorities are in the position of "playing catch up" to the waste streams and potential hazards from them long after their use has had *de facto* authorization.

Issues of physical and chemical properties are secondary to these countries, however a carefully planned legislative effort, whenever it is begun, can restrict the types and quantities of radioactive materials allowed for use in the country. This will serve to directly limit the eventual waste management problems arising from their use. An example would be prohibition of the use of organic cocktails for scintillation fluids, thus eliminating this type of waste that is difficult to treat.

3.2. SCALE OF TECHNOLOGY APPLICATION

This criterion is driven by the volumetric arisings and holdings of waste. The quantity of waste and its rate of generation will also have a considerable influence on the scale and design of the waste management facility. 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. If waste quantities are large and there are constraints on the size of the waste management facility, volume reduction could be justified. In general, large quantities of waste will require specialized, potentially more dedicated facilities and equipment. These facilities can be constructed in situ, or in some cases hired (e.g. mobile supercompactor). Small volumes of waste, on the other hand, will require simpler 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 spent radioactive sources for disposal) or new processes for which extrapolation to a large scale application may need more development and evaluation. Other processes are characteristically large scale, such as supercompaction of solid waste, evaporation of aqueous effluents, etc.

Embodied in the scale of application is a choice between a central treatment facility to which waste is transported, a facility or facilities co-located with the waste production sites (i.e. possible duplication of facilities) or moving a portable unit to generating sites. This choice will be dictated in turn by non-technical factors such as cost, transport regulations, etc.

Some equipment may have limited throughput, for example, monitoring time that is bounded by physical size and residence time. Choices in the case will be for alternative monitoring arrangements or multiple parallel units.

The quantity and type of waste generated in each of the 128 Member states will depend on the type of activity and the scope of their commitment to the use of radionuclides and generation of nuclear power [12, 13]. Very rough estimations of some typical waste arisings are shown in Table III for SIA, MIA, RRA, NPP and NFC countries. It should be noted that the amounts of waste generated are not necessarily linked to a number of research or power reactors in the country but rather related to the size of its population (in case of medical use of radionuclides) and the general level of its development (a number of hospitals, research centres, industrial enterprises, etc.). Table IV shows typical arisings for major waste producers in NPP and NFC countries.

TABLE III. TYPICAL ANNUAL WASTE ARISINGS FROM HOSPITALS, INDUSTRIES AND RESEARCH IN MEMBER STATES.

Waste types	**SIA countries**	**MIA countries**	**RRA countries**	**NPP countries**	**NFC countries**
Spent sealed sources	2–10	10–50	20–100	50-1000	>1000
Scintillation liquids	Few liters	10–20 L	20–50 L	50- 200 L	50–1000 L
Solid compactable waste	< 1 m^3	1–3 m^3	50–100 m^3	>1000 m^3	>1000 m^3
Solid non-compactable waste	-	-	1–3 m^3	2–20 m^3	>100 m^3
Aqueous waste including decontamination waste	< 10 L	1–2 m^3	2–200 m^3	300–1000 m^3	>100 m^3
Organic liquid waste including oils, lubricants, extraction agents, solvents	< 10 L	10–20 L	0.1–1 m^3	1–10 m^3	10–100 m^3
Biological material	-	-	0.1–0.5 m^3	0.1–5 m^3	1–10 m^3
Spent ion exchange resins	-	-	0.5–1.0 m^3	0.5–3.0 m^3	1–10 m^3
Spent fuel elements (total after 8–10 years)	-	-	0.5–1 m^3	0.5–2 m^3	0.5–10 m^3

3.3. ANTICIPATION OF FUTURE NEEDS

The future usage of equipment and facilities will influence the selection of an appropriate technology. It might, for example, be appropriate to construct temporary facilities or hire services to manage existing waste. This might be complemented at a later date by more permanent facilities to manage future waste arisings. Alternatively, a modular waste management facility might be required, that can be expanded to meet future needs. Simple modular designs can be readily expanded to accommodate new equipment and processes or simply to increase capacity of an existing process or a waste store.

In simple terms the choice will depend on if the technology is driven by a short-term need or is part of a long-term strategy related to the uses of radionuclides or nuclear power.

3.4. MATURITY OF THE 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 and questions such as:

- Is the process an applied technology or still at the R&D stage?
- Has it been demonstrated (with surrogates or real waste)?
- Has it been licensed or is it licensable?
- Is the technology currently in use?
- Are designs available and can suppliers be identified?

- What is the practical operating experience (cost, throughput, reliability, compliance, maintainability)?
- Is there access to information regarding the current uses of the technology to verify suppliers' claim and identify any problems experienced in use?

For all application of technology in the nuclear and radiochemical industries there are advantages in reducing cost and risk by using mature technologies and avoiding first of a kind

TABLE IV. TYPICAL ANNUAL WASTE ARISING FROM THE NUCLEAR FUEL CYCLE

Stage	**Waste type**	**Quantity $m^3/GW{\cdot}a$**
FRONT END		
UF_6 conversion	Liquids, solids	50
UF_6 enrichment	Gaseous, liquids, solids	25
UO_2 fabrication	Liquids, solids	75
MOX fabrication	Liquids:	
	- suspect	0.64
	- contaminated	5
NUCLEAR POWER PLANT OPERATION		
Evaporator concentrates	Liquids	50
Filter sludges	Liquids	10
Ion exchange resins	Solids	2
Decontamination concentrates	Liquids, solids	10
Absorber rods, neutron sources, etc.	Solids	0.1
Others	Solids	260
BACK END		
Reprocessing		
Hulls/hardware	Solids	15
Feed sludge	Solids	0.02
Tritium containing effluents	Liquids	70
HLW	Liquids	28
ILW	Liquids	25
LLW	Liquids	15
	Solids	65
Once through		
Fuel assemblies (t/U)	Solids	30
Decommissioning of fuel cycle facilities (conditioned waste)		
UF_6 conversion	Solids	0.5-1
UF_6 enrichment	Solids	5
UO_2 fabrication	Solids	1-2
Power plant	Solids	375
Reprocessing	Solids	5

processes, over sophisticated solutions and avoiding extensive development programmes. This is particularly true for generators of small volumes of waste who can benefit from “Best Practice” built up from many years experience where use of mature technologies (those with a good track record) will bring low risks and lower costs.

3.5. ROBUSTNESS OF THE 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 (e.g. slurries, combustible and non-combustible solids, aqueous waste concentrates, ion exchangers);
- 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 and end-products, and local availability of other treatment technologies. Since the pretreatment intervention is costly and may lead to additional personal exposure, robustness, even if it is adequately defined, is an important criterion in the selection process.

The concept or robustness can be illustrated in the following example for an incinerator:

- What can it accept for incineration?
- Is it necessary to remove metals or other unsuitable materials?
- Can it take waste of low calorific value?
- Can it incinerate both solids and liquids?
- Will the product ash be stable and meet disposal WAC, or will its conditioning be necessary?
- Can the off-gases be treated?

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

3.6. RANGE OF TECHNOLOGY APPLICATION

Whilst robustness covers the sensitivity of a process or technology to the waste stream, “range of application” 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 (e.g. PCBs and PAHs) and can operate at low capital cost whilst an incinerator can destroy virtually all organic materials but carries a relatively high capital cost.

This criterion addresses to a balance between a small simple specific technology which the generator of a single waste stream might resort a larger, more versatile unit that might be used at a central treatment facility for a multi-waste generating country.

The field of application will also influence the technologies selected, for example a waste that can readily be handled can use simple manually operated technologies. A high level waste will require substantial levels of shielding which in turn may imply the use of low maintenance systems and remote handling technologies. Waste bearing high levels of α-contamination may require technologies that can be deployed in gloveboxes or contained cells.

3.7. TREATED PRODUCTS CHARACTERISTICS

A factor that will be influential in the choice of technology is the product from the process itself. This product may be for:

- further treatment;
- direct disposal;
- immobilization for disposal;
- immobilization for storage;
- interim storage;
- packaging for transport or disposal.

The product requirements, effectively the process specification, will be influenced by the disposal option, future conditioning steps, storage time, transport regulations, etc.

A specific product definition is the WAC which will be defined against a particular disposal option, for example factors such as package type, dimensions and performance (drop tests, etc.) might be specified. The leachability of the waste form might be defined together with its form and appearance (e.g. homogeneous, monolithic). The WAC may also define the surface dose which in turn will dictate, for example, the level of shielding requirements.

3.8. COMPLEXITY AND MAINTAINABILITY

Complex technological processes are not automatically better than simple ones. The principles of simplicity of design and operation of are particularly important in the nuclear industry. Features that such process might exhibit are:

- few or no moving parts;
- commonly available reagents for use;
- stable process, easy to control;
- no need to have an exceptional level of technical competence to operate;
- easily accessible components.

The penalty for a complex process is often high capital and operating costs and lower plant availability due to maintenance needs. The technical factors that will influence maintenance (including for example, removal, decontamination, repair, replacement, etc.) and the process down time might be:

- Simplicity.
- Radiation resistance (hardening).
- Corrosion resistance.
- Wear resistance.
- Contamination resistance.
-

Failure to consider these factors may well result in unacceptable system failures and down-time.

3.9. VOLUME REDUCTION

There are two components of waste volume reduction. The first is the reduction of volumetric waste arising in the waste generating processes [14]. The second component of volume reduction is related to treatment of generated waste to reduce its bulk in order to benefit from reduced packaging, transport and disposal costs.

Volume reduction tends to be more an issue for large volume waste producers while for small volumes the cost of the treatment facility, the secondary waste arisings and the decommissioning waste from closing the facility may not off-set any short-term gains.

3.10. STATE OF RESEARCH AND DEVELOPMENT

All technologies used in the nuclear and radiochemical industry have been underpinnned by extensive R&D programmes and indeed any new or one of a kind process will require extensive development to support design and licensing. R&D programmes are, however, expensive and demanding of highly qualified staff. With the deployment of many technologies worldwide (i.e. mature technologies), often proven and robust processes the use of "Best Practice" will limit the scope and even need for R&D. Choice of an "immature technology" will automatically involve some R&D investment.

For small and limited producers of waste scientific investigation may be limited to ensuring the waste is compatible with the process (by carrying out treatability tests or characterization of waste) and even this service could be contracted in.

3.11. SECONDARY WASTE AND COMPATIBILITY WITH EXISTING PROCESSES

There is a tendency to consider processes and technologies in isolation. No applied technologies are without their own requirements and few can be operated without secondary waste generation. The upstream processes, the support services and the secondary waste must all be considered and provision made in planning and selecting technologies either providing additional equipment or utilizing existing equipment.

An example is incineration which can be used to destroy organic materials and reduce waste volumes. However, to support the incinerator itself it may be necessary to consider the following associated processes:

- feed characterization (radiometric analysis);
- feed preparation (removal of items such as gas bottles and shredding the waste);
- process control;
- criticality control (for fissile material incinerators);
- assay of the ash;
- ash immobilization;
- treatment of filters;
- treatment of liquid waste from off-gas systems.

All of these additional processes add to the cost, the complexity and the waste that must be disposed of.

3.12. SAFEGUARDS AND NUCLEAR SAFETY

The technical factors in this section are of particular importance to NPP and NFC Member States where the waste containing fissile materials is to be processed. Typically these criteria will include:

- an ability to confirm the concentration and quantity of fissile material throughout the process (e.g. accountancy tank);
- control of fissile mass in a unit process by geometry or fissile content monitors;
- shielding;
- containment;
- restriction of access.

3.13. SITE AVAILABILITY AND LOCATION

Site availability and location have implications for both waste treatment and disposal. Factors that must be taken into account are socio-economic (see Section 2.8) and technical. Technical factors will include the geology, hydrogeology, hydrogeochemistry, seismicity, climate, the proximity of natural resources (mineral, drinking water, forests, etc.), the proximity of raw materials (water, power, personnel, etc.). The technology choices will depend on the availability of sites and Member States, in their planning processes, dedicate a significant degree of effort to selecting a site that is both fit for purpose and technically acceptable. The types of technical decisions made against these criteria might, for example, be a greater reliance on engineered barriers for groundwater control in an area with a significant groundwater flow than a site in an arid region. It should be noted that these factors will be taken into account in any performance assessment of a site or activity.

3.14. POTENTIAL FOR INTRUSION

As with site selection intrusion is an issue both for operating sites (inadvertent or malicious access to facilities) and disposal sites (largely inadvertent access to waste by mining, drilling, water extraction, geological survey, etc.).

The response might include a security system for operating a site. For a repository that has been closed, massive barriers (engineered) in geological remoteness might be appropriate.

4. WASTE MANAGEMENT STRATEGIES

A strategy for management of radioactive waste would basically be a function of a national policy. Such a policy has to be implemented through a legal framework. Generally, the policy and the legal instrument would only relate to the need to protect the environment and the public and towards this purpose stipulate the limits of what will be permitted for release in terms of radioactivity, radiotoxicity and, in some cases, chemical and biological toxicity. In order to meet such stipulations, it will be necessary for the organization responsible for radioactive waste management, to evolve a strategy by the selection of one or more technologies available to manage the waste. Ideally, the strategy should be determined before the system is put in place. In practice, one strategy, or a mixture of strategies exists. Their selection and use should be formalized to enhance the safety and effectiveness of the overall system. Examples of waste management strategies include on-site management of the waste, centralized management, and a mixture of these two. An additional possibility is international co-operation in the conditioning, treatment, packaging, storage and/or disposal of waste.

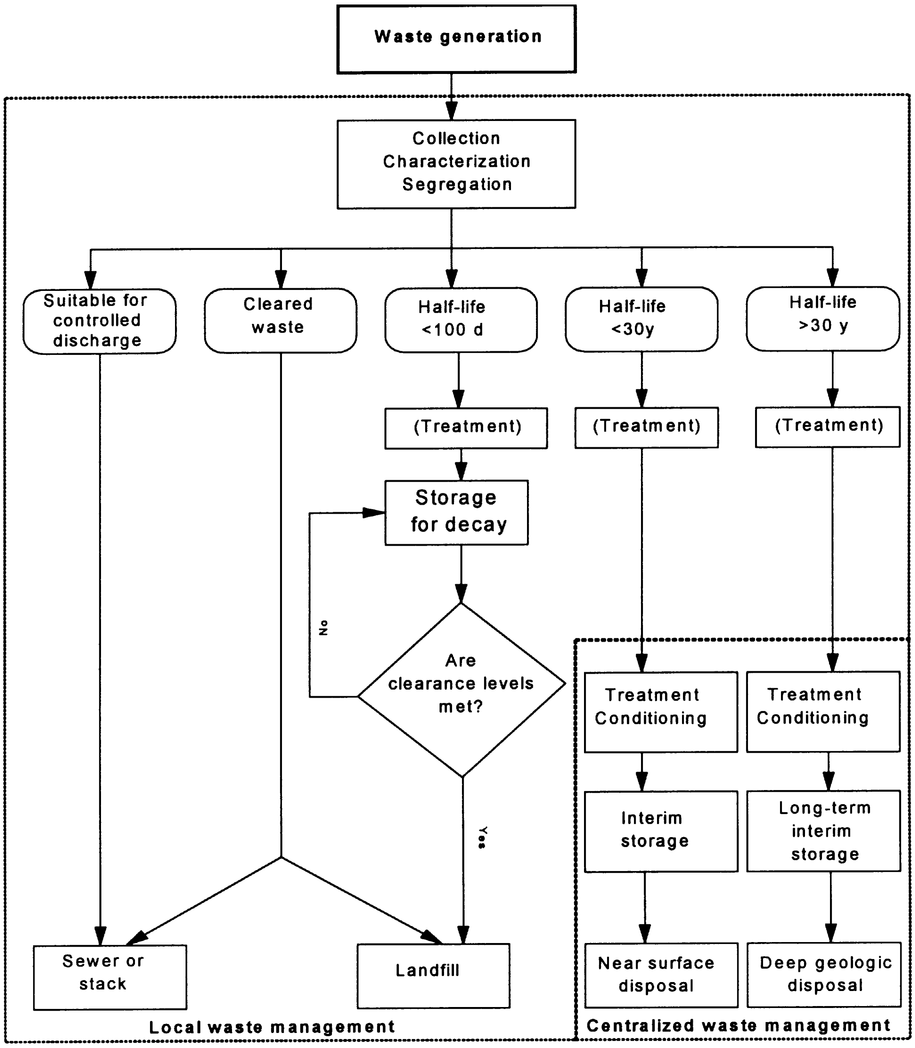

FIG. 3. Local and central waste management strategies.

On-site management of waste from 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 disposal. This waste management strategy eliminates the hazards associated with transportation to centralized facilities, however it involves the development and maintenance of redundant capabilities for waste management for each facility operating under this scheme. Also, if disposal is not permitted locally, on-site storage is mandatory and accumulation of waste with concurrent safety problems may become a problem. This strategy may be recommended to SIA countries for economic reasons as long as the primary safety considerations noted in Section 2.3 are not compromised.

Centralized waste management takes many of the waste management steps and includes 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. At some point in its development, MIA countries or countries with a greater level of use of nuclear energy may have to consider the concept of centralized management in order to control the safety and minimize economic impacts of radioactive waste on the country. Generators will then be required to prepare waste according to specifications developed for transport of the waste and criteria for acceptance of waste by the central facility. This facility, depending on the strategy developed by the Member State, may take over responsibility for the waste including processing and storage. If and when a disposal facility becomes available, the stored waste will be transferred there under the direction and control of the centralized processing/storage facility.

Some 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 disposed of as non-radioactive waste. While its generation, storage, and eventual disposal should be overseen and regulated, it is generally not beneficial to transport it to a central location unless the security of the waste is a problem.

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 total activity and half-life, could be introduced, as mentioned earlier (see Fig. 3). Extra-national services for waste treatment and packaging may also be considered, if the capability within its own borders cannot allow the country adequately manage an existing or projected waste stream.

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 consideration of a variety of technical and non-technical factors (see Sections 2 and 3) before opting for a particular technology or a combination of technologies. It is likely that one or some of these factors may play a decisive role. Given below is a typical list of steps and factors that are commonly considered before a selection of technology is made (Fig. 4).

As the cost of waste management will be directly proportional to the quantity of waste, there will be an economic incentive to minimize the quantity of waste arisings.

If radionuclides in the generated waste are so short-lived, as in the case of some medical applications of radioisotopes, mere delay and decay could be the right approach; in this event no special technology is called for. If, however, the volume of such a waste is considerable, adequate storage capacity to hold the waste and permit its decay, will be necessary. Depending on the national policy and the regulatory requirements, it may be possible to dispose of the waste as non-radioactive if radionuclides have been decayed to below approved clearance levels.

If a waste generating activity (e.g. operation of reactors) is such that there is a need to go through pretreatment, treatment and conditioning steps leading to disposal of the waste in a repository, factors which are socio-political in nature, availability of trained personnel, other physical infrastructure components and the question of cost need careful evaluation. In case of management of reprocessing HLW or conditioning of spent fuel, the important aspect of public acceptance towards the disposal option may play a dominant role.

The extent to which waste management efforts are considered necessary is essentially based on what nuclear activity is being pursued in a country. In the case of a SIA country, it is clear that efforts involved would be minimum and so not requiring adoption of any complex technology. With multiple isotope applications, it would only be the volume of waste and its diversity in nature that would increase but not calling for any significant increase in terms of technology inputs for managing the wastes. 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, till a disposal option becomes inevitable. If a country chooses to operate nuclear power plants for producing electricity, it is expected that a considerable degree of technological competence would prevail for management of both spent fuel and radioactive wastes. If the country wants to proceed further with either reprocessing the spent fuel or conditioning the spent fuel for direct disposal, it should carefully examine the technological infrastructure available either within the country or made available to it from abroad. This is due to the commitment that may have to be made for isolation of HLW (either from reprocessing or from spent fuel conditioning) from the biosphere for several thousands of years.

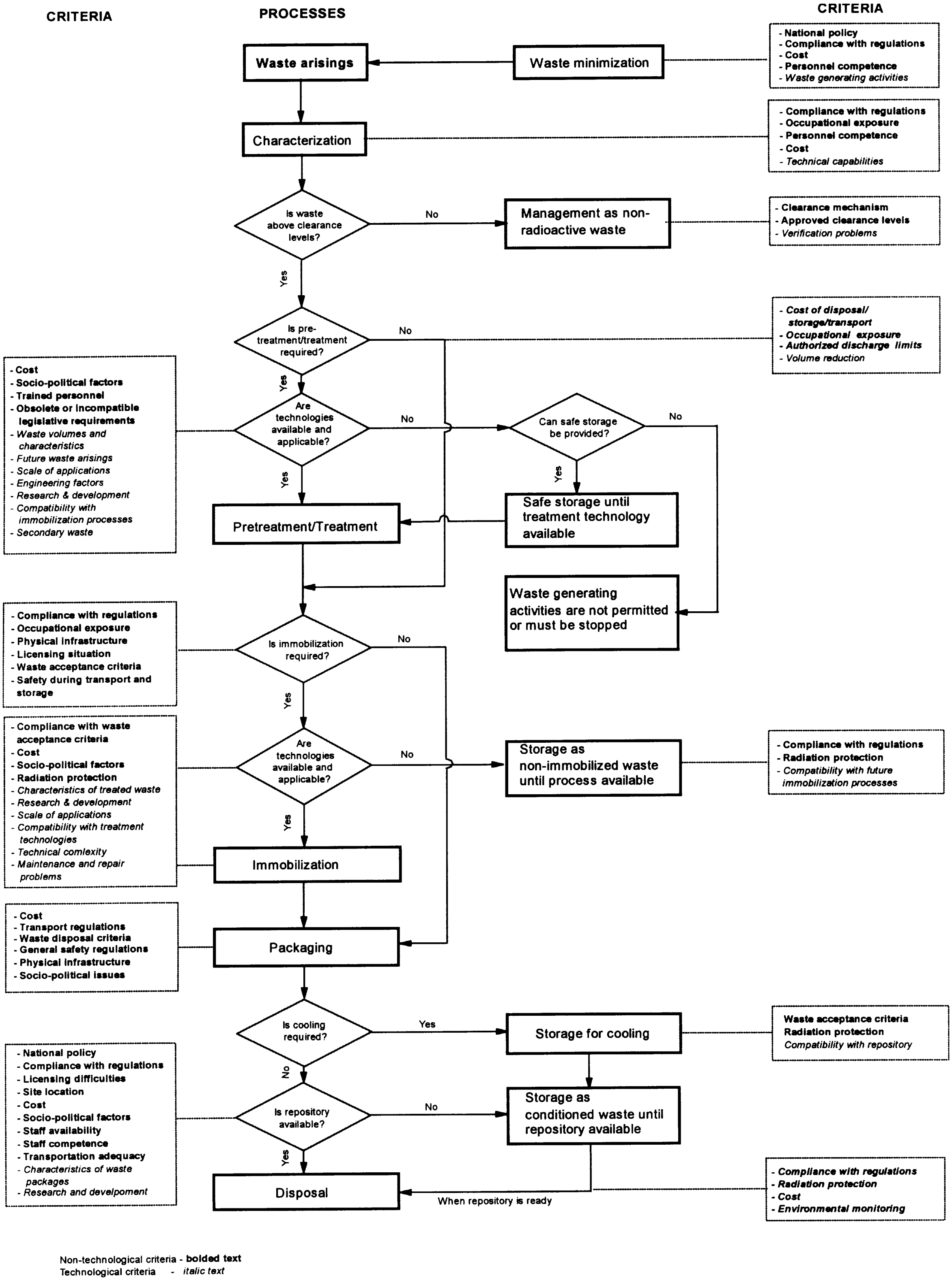

FIG. 4. Decision tree concerning the selection of a waste management technology.

Thus it would be seen that what needs to be done and what it takes to do it, in respect of radioactive waste management, is graded from minimal efforts to highest levels of contemporary technology,. the subject being what nuclear activity is being pursued in the relevant country.

5. WASTE MANAGEMENT TECHNOLOGY OPTIONS

5.1. WASTE MANAGEMENT PLAN

The basic steps of the radioactive waste management system are given in Fig. 5. To achieve satisfactory the overall safety goal of waste management, component steps must be complementary and compatible with each other. In this respect it is particularly important that no step should preclude later effective waste management operations. The core of the waste management system is the technology which is applied to a waste from its generation to its disposal.

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 final destination. As defined by the national law and regulations, the operator has to use this plan as support for any application to the Regulatory Body for the issue of an authorization or a licence to generate and/or manage the waste.

In establishing the waste management plan, a range of technological options shall be identified and evaluated in order to select and justify the most appropriate solution by taking into account the basic waste management principles, regulatory requirements, resources available, waste acceptance criteria, transport regulations, and any other constraints described in more detail in Sections 2 and 3. The selection of a technology for each step is necessarily bound up with the selection of an overall plan for the management of the waste under consideration, and this in turn may be part of a larger scheme embracing many waste types. The technological options available for various liquid, solid and gaseous waste are briefly described in the following sections.

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, that the 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 waste acceptance criteria for disposal.

5.2. PRETREATMENT

Pretreatment involves a variety of activities applicable to liquid and solid radioactive waste and can be defined as any or all the operations preceding waste treatment [15]. The main objectives of pretreatment are to:

- Segregate waste into active and non-active streams.
- 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.
- Recover products for recycling.

Benefits of pretreatment are improved safety, lowered radiation exposure and significantly lower costs in subsequent waste management operations. These benefits must be balanced to 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 importance to pretreatment should create positive impact throughout the rest of the waste management cycle. The main considerations in the selection of pretreatment methods are:

- radiological protection standards and objectives;
- waste minimization;
- availability of pretreatment technologies;
- economic factors;
- requirements for the further treatment, conditioning, storage, off-site transport and final disposal of the waste.

5.2.1. Up-front waste characterization

The success of treatment and conditioning depends largely upon the knowledge of 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, better characterization 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. Essentially for prepackaged waste, characterization may cause significant exposure of the operators, consequently, there is a need for better and fast-non-destructive inspection methods. Given the high cost of detailed characterization and processing with robust technologies, there may also be room for optimization.

Characterization of historic waste (often stored in drums) is a difficult and costly task whereas such problems might have been avoided by more adequate characterization at the time of generation. This certainly contains a lesson with regard to future waste generation.

The radionuclide inventory in waste can be characterized by calculation, dose rate or key nuclides, relatively easy procedures are currently applied for determination of the activity content of waste [16]. These procedures are based upon knowledge of the processes from which the waste arises and the correlations between the main radionuclides involved. By evaluation to full scale geometry, including the package size and density of the waste material, the gamma dose rates on contact with the primary package can be correlated to the activity content. Nevertheless, long-lived radionuclides are important in waste disposal and it is a complex matter to determine the inventories of most of these radionuclides.

For materials that are contaminated, which is often the case with general trash, assessment of surface contamination is best obtained by direct measurements using alpha, beta or gamma survey instruments coupled with surface smears over a 100 cm^2 surface, as is standard practice at most facilities.

5.2.2. 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 a waste management system.

The following are the main criteria in planning the segregation of waste:

- physical and chemical 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.

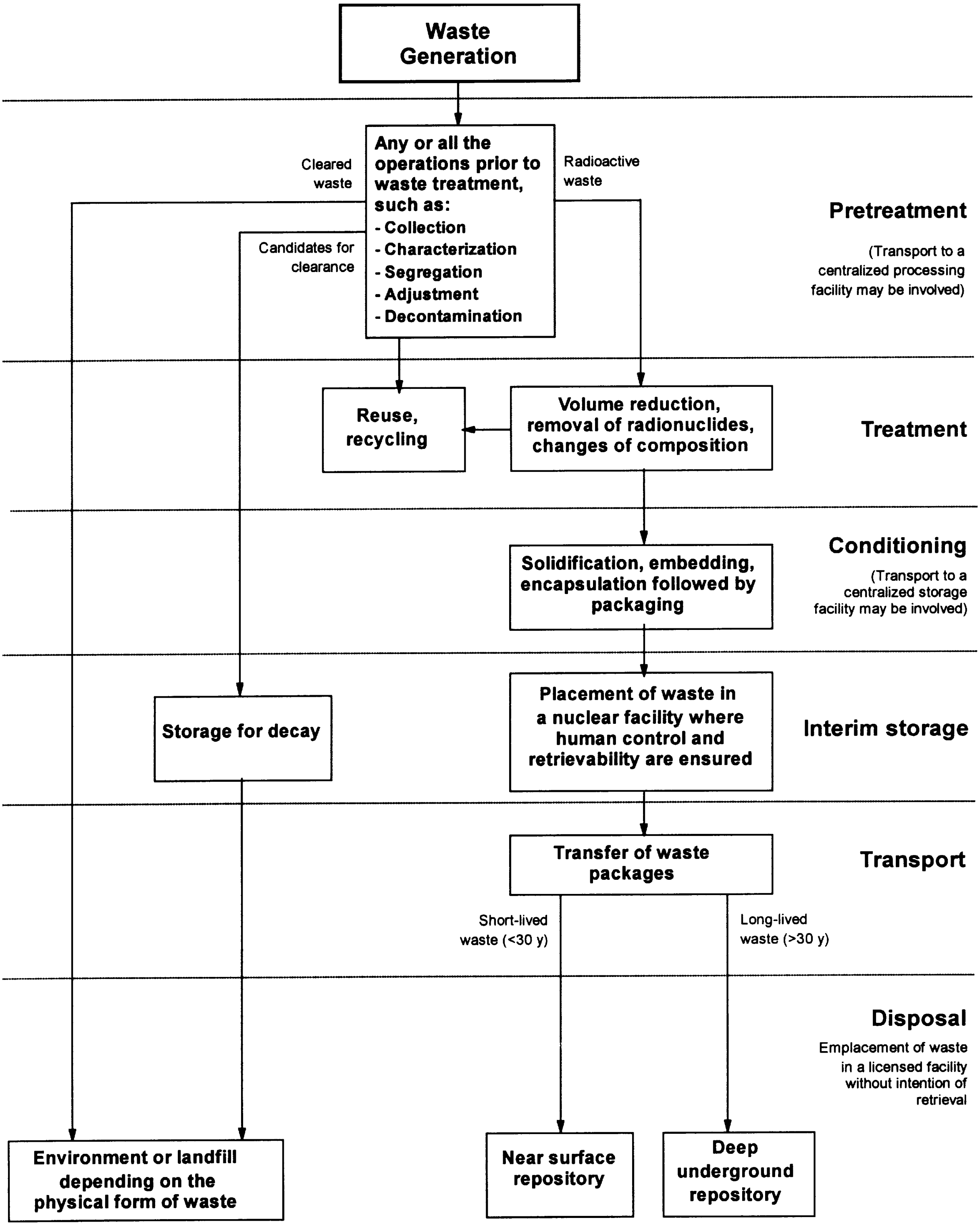

FIG. 5. Waste management steps.

The chemical composition of liquid waste, may affect, for example, the collection and segregation strategy through its impacts on the following:

- corrosion of storage tanks or equipment used for further waste processing;
- possible evaporation factors;
- efficiency of ion exchange processes;
- toxic nature of the waste;
- safety of treatment or conditioning processes (e.g. prevention of violent reactions between organic materials and nitric acid);
- blockages due to solids content.

In general the efficiency or applicability of further waste processing must be considered in the selection of proper segregation strategies, for example the content of combustible materials in case of incineration or separation of liquid and solid waste forms in case of compaction.

Plants and procedures for segregation operations are generally custom designed to specific requirements but all the necessary technology, tools for waste handling, and packaging equipment are commercially available.

5.2.3. Chemical adjustment

In many cases it may be necessary to adjust the chemical composition of liquid waste to ensure its compatibility with subsequent interim storage, treatment or immobilization processes. The most common procedures are:

- acid or alkaline adjustment for interim storage, evaporation, ion exchange or disposal;
- removal of ammonia by alkaline distillation prior to bituminization;
- destruction of oxalates in decontamination solutions;
- use of alkaline earth ions to modify the behavior of conditioned waste;
- destruction of nitric acid by the use of organic compounds;
- electrolytic destruction of organic acids, such as oxalic acid, to reduce corrosion before evaporation.

Although the chemistry of the reactions involved in such processes is generally well understood and information is likely to be readily available, its translation into plant and equipment which can be routinely operated safely and in conformity with radiation protection standards is likely to require demonstration of the process on a significant scale and the application of special project engineering and design skills.

5.2.4. Physical adjustment

Process effluents may contain entrained organic solvent or other materials such as lubricating oil, and these may require their removal at source or at a central collecting facility. Organics forming a separate phase may become subsequently attached to oleophylic debris (e.g. plastics and string) in the effluent or attract fine active solids. A wire packed column may be used to promote coalescence of organic liquids and removal may be effected by settlement in a tank or inclined plate separator. Filtration of any fine particulate by precoat or sand bed filtration is likely to be essential before any effluent treatment by ion exchange.

5.2.5. Size reduction

Size reduction techniques are used either to facilitate economic packaging for transportation or to prepare the solid waste for subsequent treatment. Methods that are considered as typical pretreatment are dismantling of structures or components in case of decommissioning (taking apart and/or cutting into pieces) or shredding. Shredding of solid waste, either is a prelude to incineration or cementation, or a size reduction method for non-combustible waste. This operation can be done at the site of the waste generator to reduce transport frequency or in a central waste processing facility to improve treatment performance (e.g. incineration).

Dismantling involves operations normally used for construction or demolition, with additional constraints for controlling radioactive contamination. Techniques for dismantling typically include mechanical and thermal methods.

5.2.6. Packaging

Packaging of solid radioactive waste by the waste generator for handling, transportation and further waste processing is an important pretreatment operation. It has to comply with transport regulations (if transportation is involved), acceptance criteria or waste specifications for further waste processing, and general occupational radiation protection standards.

Combustible low level solid waste is normally collected at the origin in transparent plastic bags (polyethylene or PVC) with sheet thickness between 0.1 and 0.2 mm and volumes of 15–50 L, and often marked with the radiation symbol. This primary package is generally adapted to the collection system, which may be pedal bins for laboratories and other small waste generators or larger bins at nuclear facilities. After filling, the plastic bags are removed from the bins and closed with an adhesive tape.

Non-combustible small size LILW are usually collected as compressible and non-compressible materials in metal or cardboard boxes of 20–50 L for small generators and metal drums of 100–200 L for larger generators. Standard HEPA filters are often packed in welded plastic bags. Cardboard boxes may be used as an overpack.

Deep freezing of animal carcasses or similar types of waste is used to allow convenient accumulation and storage. Carcasses are packed in plastic bags before freezing.

5.2.7. Decontamination of solids

Decontamination of solid waste (e.g. tools, instruments and plant items) is most commonly employed with the objective of reuse. However, it may also be employed to reduce contamination to levels acceptable for disposal as non-radioactive waste, to minimize personnel exposure during subsequent waste treatment operations or for product recovery.

Decontamination is only beneficial where the value of the recovered object or advantage gained is greater than the cost of the decontamination process and the treatment, conditioning, transport and disposal of the secondary waste produced. The exposure of operators involved in decontamination operations must also be taken into account.

The technology of decontamination has been widely studied and a large variety of methods are well established. The main techniques are:

- manual cleaning;
- vibratory cleaning;
- machining, grinding and chipping;
- vacuum cleaning;
- chemical baths;
- circulation of cleaning solutions through plant systems;
- melting with slag separation;
- electropolishing;
- ultrasonic cleaning.

5.2.8. Pretreatment of aqueous waste and sludges

The most common methods for pretreatment of aqueous waste and sludges are sedimentation and decantation and/or filtration. These processes may be beneficial, if a separation of waste streams for further processing is justified from economic or radiation protection reasons.

The main features and limitations of these pretreatment methods are shown in Table V.

5.3. TREATMENT

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

- Volume reduction.
- Removal of radionuclides from the waste.
- Change of composition.

After treatment, the waste may or may not be immobilized in the course of conditioning to achieve an appropriate waste form.

5.3.1. Aqueous waste

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

(a) a small stream of concentrate containing the bulk of radionuclides; and

(b) a large stream, the level of contamination of which is sufficiently low to permit its discharge to the environment.

A treatment process cannot be assessed only for its ability to decontaminate the liquid waste stream. It must be remembered that treatment is part of an overall waste management (see Fig. 5) in which waste generation, conditioning and final disposal all play important parts. The selection of a liquid waste treatment process involves a set of decisions related to a number of factors (Sections 2 and 3). These can be grouped into five main categories:

- Characterization of arisings with the possibility of segregation.
- Discharge requirements for decontaminated liquors.
- Available technologies and their costs.
- Conditioning of concentrates resulting from the treatment.
- Storage and disposal of the conditioned concentrates.

TABLE V. MAIN FEATURES AND LIMITATIONS OF THE PRETREATMENT METHODS

Pretreatment methods	Features	Limitations
Collection and segregation	• Enables waste characterization. • Separates incompatible waste. • Minimizes radioactive waste volume. • Enables recycle/reuse of material .	• Additional dose for personnel. Member States are encouraged to conduct segregation at the point of waste generation to avoid the potential mixing of waste streams that make subsequent treatment more difficult or expensive.
Chemical adjustment	• Neutralize and solidify liquid waste. • Prepare waste for encapsulation in a matrix (e.g. bitumen, cement or glass). • Destruction of organics and corrosives that shorten package or equipment life.	• Some technologies are too complex and/or expensive for developing countries. • Generation of waste requiring this kind of treatment should be limited to match compatible Member State technologies.
Physical adjustment	• Removal of organics from liquid waste. • Allows treatment by ion exchange resins.	• Feature of more complex processes in countries with nuclear fuel cycle facilities. New process applications may avoid generation of this waste.
Size reduction	• Enables use of one size of container for most applications. • Reduces transport risk. • Minimizes volume.	• May not be applicable for small generators.
Packaging	• Packaging in plastic bags is typical at the point of generation, followed by placement in a container suitable for disposal. • Prevents spread of contamination. • Enables transportation for treatment, conditioning, storage, and/or disposal.	• Organic waste, including animal carcasses, must undergo additional treatment steps prior to disposal. • Excessive handling for the purpose of repackaging should be avoided.
Decontamination	• Waste minimization for recycle/reuse • Cost/benefit analysis is required • Application to projects involving decommissioning	• The decontamination practices are often not economically and technically feasible for small waste generators.
Decantation, Filtration	• Easily applicable to aqueous waste and sludges	• Secondary waste will be generated • No separation of dissolved materials • Processing of separate waste streams necessary
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

Figure 6 is a flow sheet that summarizes the decision making process involved in the selection of an aqueous waste treatment process. The processes available for treatment of aqueous waste fall generally into three main categories: chemical precipitation, evaporation and ion exchange.

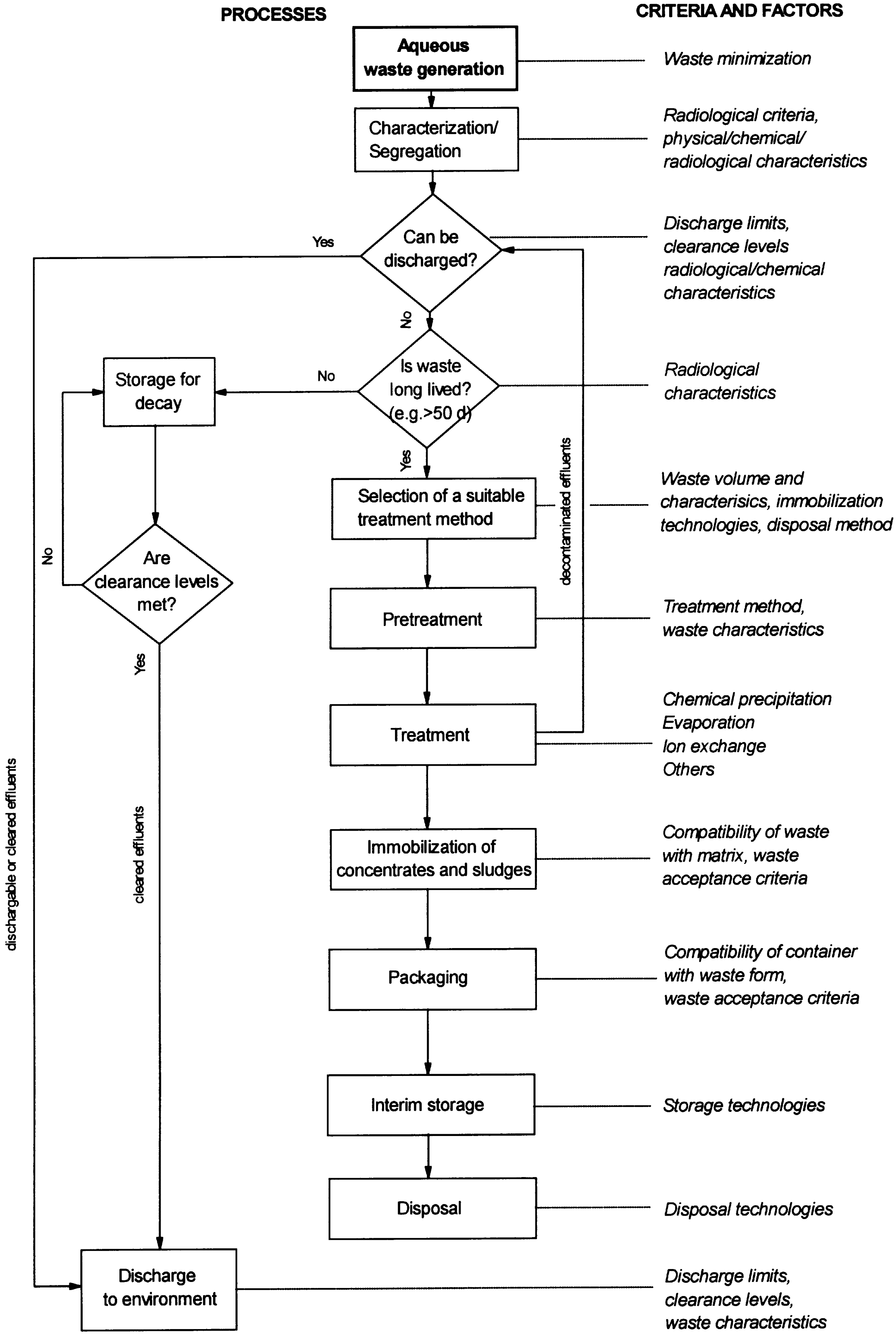

FIG. 6. Management flow diagram for aqueous waste.

5.3.1.1. *Chemical precipitation*

The objective of a *chemical precipitation* process is to remove radionuclides from liquid waste by the use of an insoluble finely divided solid material. The insoluble material or floc is generally, but not necessarily, formed in situ in the waste stream as a result of a chemical reaction A typical chemical precipitation method involves four main stages [17]:

(a) the addition of reagents and/or adjustment of pH to form the precipitate;

(b) flocculation;

(c) sedimentation;

(d) solid-liquid separation.

The use of these processes concentrates the radioactivity present in a liquid waste stream into a small volume of wet solids that can be separated from the bulk liquid component.

Chemical precipitation may be affected by the presence of such components of the waste stream as complexants, trace organics or particulates. In these cases, pretreatment may need to be added to the main process. When the waste stream composition is variable in nature, either in its radioactive or in its non-radioactive content, a single chemical precipitation process may be inadequate. A combination of specific treatments is frequently necessary to achieve the best overall decontamination factor for total alpha and/or total beta-gamma activity of the liquid waste. Combination of processes can be used as a multistage batch process or as a continuous precipitation process and will produce one or several sludge streams for further conditioning and storage or disposal.

The precipitation process produces sludge as a result of the reactions taking place during chemical treatment steps and has always to be connected with physical methods for separation of sludge and liquids. It should be noted that, depending on the levels of radioactivity in the primary waste and on the concentration factors achieved, the sludge produced by a chemical treatment may be highly radioactive. Therefore, this should be carefully considered during the design of the plant by making provisions for adequate shielding around sludge containing components.

The waste volume reduction and the decontamination factors achieved with a precipitation process strongly depend on the method of solid-liquid separation used. Various possibilities include sedimentation and decantation, filtration or centrifugation. The choice applied should depend on the volumes to be treated, on the quality of the precipitates, on technical feasibility and cost. For treatments of up to 100 m^3/year, the simple sedimentation and decantation technique may be considered the most suitable process for separation of sludge and liquids. Laboratory work may be required to determine optimum precipitation and separation conditions. The main problem is that most iron bearing precipitates are notoriously difficult to filter because of their gelatinous nature and a special expensive filtration plant may be needed. However, provided that the final filtrate is pure enough for discharge without further treatment the process is much cheaper than evaporation.

Chemical precipitation processes are well established methods for the removal of radioactivity from LILW and are in regular use at spent fuel reprocessing facilities, research establishments and nuclear power stations. Processing by chemical precipitation is used normally to treat high volume, low level waste streams or if more efficient treatments, such as concentration by thermal evaporation or ion exchange, are not available or possible (for example, when the salt load of the waste or the suspended solids content is high). Alternatively, a precipitation process can precede another treatment technique such as ion exchange or evaporation. Because of the extensive experience already gained over many years in the treatment of radioactive liquid waste by chemical precipitation, maintenance of equipment should not pose any unusual problems. Corrosion is, however, a point to be carefully considered because of the extensive use of a wide range of concentrated chemical reagents over a broad spectrum of pH values.

5.3.1.2. Evaporation

Evaporation is a proven method for the treatment of liquid radioactive waste providing both good decontamination and good concentration. Water is removed in the vapour phase of the process leaving behind non-volatile components such as salts and most radionuclides. The technique is well developed and both its advantages and disadvantages are well understood.

Evaporation of liquid radioactive waste by filtration and/or decantation with lower salt content (1–5 g/L) is normally carried out in two stages. Decontamination is performed in the first stage and concentration in the second stage. In the case of liquid radioactive waste with high salt content (up to 400 g/L) the process is usually carried out in one stage. Between these two methods lie the multi-stage evaporators. They can achieve high decontamination factors for large waste volumes with rather higher salt content. The presence of volatile nuclides such as tritium and some forms of iodine and ruthenium, particularly at a high nitric acid concentration, will reduce the overall decontamination factor.

For very small quantities to be evaporated pot or kettle types of evaporators are frequently used. It should be noted that recently microwave evaporation technique has been successfully demonstrated as suitable for small-scale effluent treatment operations.

Radioactive waste evaporators are generally kept simple in design to reduce maintenance problems at the expense of loss in thermal efficiency. Some wastes do, however, require more complex design and scraped film evaporators have been used for intractable low level waste. The evaporator produces a clean condensate that can be discharged to the environment and a concentrate which may be encapsulated in cement or other media for long term storage or disposal. The main disadvantages are high capital, energy and maintenance costs, corrosion, scaling or foaming. Evaporation is probably the best technique for waste having relatively high salt content and for nitric-acid-containing effluents, i.e. having a high electrical conductivity, a relatively low volume and needing high decontamination factors.

5.3.1.3. Ion exchange

This a standard method of liquid clean-up and virtually all nuclear reactors have ion exchangers. The ion exchange materials are insoluble matrices containing displaceable ions which are capable of exchanging with ions in the liquid passing through by reversible reaction. In the nuclear industry advantage is not normally taken of the reversibility and once the medium is saturated it is removed from service and treated as radioactive waste too. Substantial difficulty due to the variations of a composition of the waste streams is expected during decontamination with the wide range of radioisotopes requiring removal. There is possible sensitivity to capacity reduction due to a variety of inactive contaminants. Also any finely divided solids or colloids introduced in feed or formed during the ion exchange process may inhibit ionic transfer.

Ion exchange is a highly cost effective method of effluent treatment. Resins can often be tailor-made to suit particular applications and more work is being done in this area particularly with a view to reducing total volumes for disposal. The only problem is that of ultimate disposal, particularly of resins bearing chelating agent. A comprehensive review of ion exchange for radioactive waste treatment is given in Ref [18].

Ion exchange techniques can be used for the waste treatment purpose both in industrial and laboratory scale. New developments are mainly related to selective removal of specific ionic species from the aqueous effluents through selective ion exchange. Promising results are booked for the segregation of radioactive ionic constituents (Cs, Sr, Co) from a mixture of inorganic constituents (soluble salts, acids, etc.).

Table VI [18] is a general guide showing the main features and limitations of some available aqueous waste treatment processes. It should be mentioned that economic processes for removal of tritium in aqueous waste do not exist.

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-level in radioactivity, alkaline in pH and contains significant salt load, chemical treatment, followed by separation of the sludge, would provide adequate decontamination factor. This technology is simple and relatively inexpensive in terms of the plant and its operation but is generally limited to low level effluents. 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. As a process this is more expensive — especially when special purpose resins are used — but has a wider range of application with regard of the radioactivity concentration. There could be situations when waste volumes are somewhat high, having a low salt content but a considerably higher level of radioactivity; 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 being energy-intensive.

For each of the above methods various technological processes have been developed and widely used depending on the chemical composition of the liquid waste and the radionuclides to be removed from the bulk of waste.

5.3.2. Organic liquid waste

The volume of organic waste is small by comparison with aqueous radioactive waste, however, the risk associated with its improper management 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 goals of organic liquid waste treatment may be as follows:

- conversion to a solid form;
- conversion to an inorganic form to facilitate conditioning;
- volume reduction;
- decontamination for reuse;
- conversion to an organic form compatible with cementation.

The main features of treatment methods OF organic liquid waste have been summarized in Table VII.

TABLE VI. MAIN FEATURES OF THE AQUEOUS WASTE TREATMENT PROCESSES

Treatment processes	Features	Limitations
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 often 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
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
Solvent extraction	• Selectivity enables removal, recovery or recycle of actinides	• Organic material present in aqueous raffinate • Generates aqueous and organic secondary waste

TABLE VII. MAIN FEATURES OF LIQUID ORGANIC WASTE TREATMENT METHODS

Treatment methods	Features	Limitations
Incineration	• Decomposes organic nature of waste • High volume reduction • Combined use for other waste • Eliminates infectious hazard	• Secondary waste must be treated • High temperatures are required to ensure complete decomposition • Off-gas filtration and monitoring are required
Emulsification	• Allows embedding of liquid organic waste into cement matrixes	• Low limitations for content of emulsified liquids in the cement matrix
Absorption	• Solidifies and immobilizes organic liquids • Simple and cheap	• Suitable only for small amounts of waste • Absorbed waste may not meet disposal acceptance criteria
Phase separation (e.g. distillation)	• Removes 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

Because individual waste generators may not have expertise in the management of organic waste, and as the treatment of small quantities of organic waste may not be cost effective, it may be appropriate to consider the transportation of liquid organic waste to a central waste management facility where the necessary expertise, infrastructure and quality assurance capability can be built up.

A general flow sheet for managing organic liquid waste is shown in Fig. 7. As can be seen from a comparison of this flow sheet with the flow sheet for managing aqueous waste, treatment of large amounts of radioactive liquid organics is technology intensive as well as costly. Here is a clear opportunity for a Member State that is considering technology involving this waste as a by-product to rethink the total life cycle cost of that technology and perhaps choose an alternative.

Properly controlled incineration is an attractive technique for treating organic liquids because they are readily combustible, and high volume reduction factors can be achieved. Disadvantages inherent in using this technology are the high capital cost of the incinerator and the off-gas system, and the technical expertise required to operate and maintain the unit. Ensuring complete combustion of the waste and maintaining stack emissions within acceptable limits (which may be carefully detailed as a part of the operating licence) are the main technical difficulties for waste incineration. In addition to containing volatile radionuclides and radioactive particulates, the off-gas system must control the release of chemically toxic or noxious effluents (HCl, SO_2, NO_x). Improperly controlled combustion can produce toxic compounds, like dioxins.

After combustion, radionuclides from the waste will be distributed between the ash, filters and off-gas, depending on details of the unit's design and operating parameters. Further immobilization, such as grouting, will be required to stabilize these residues which will now have much higher radionuclide concentrations per unit volume than the original waste.

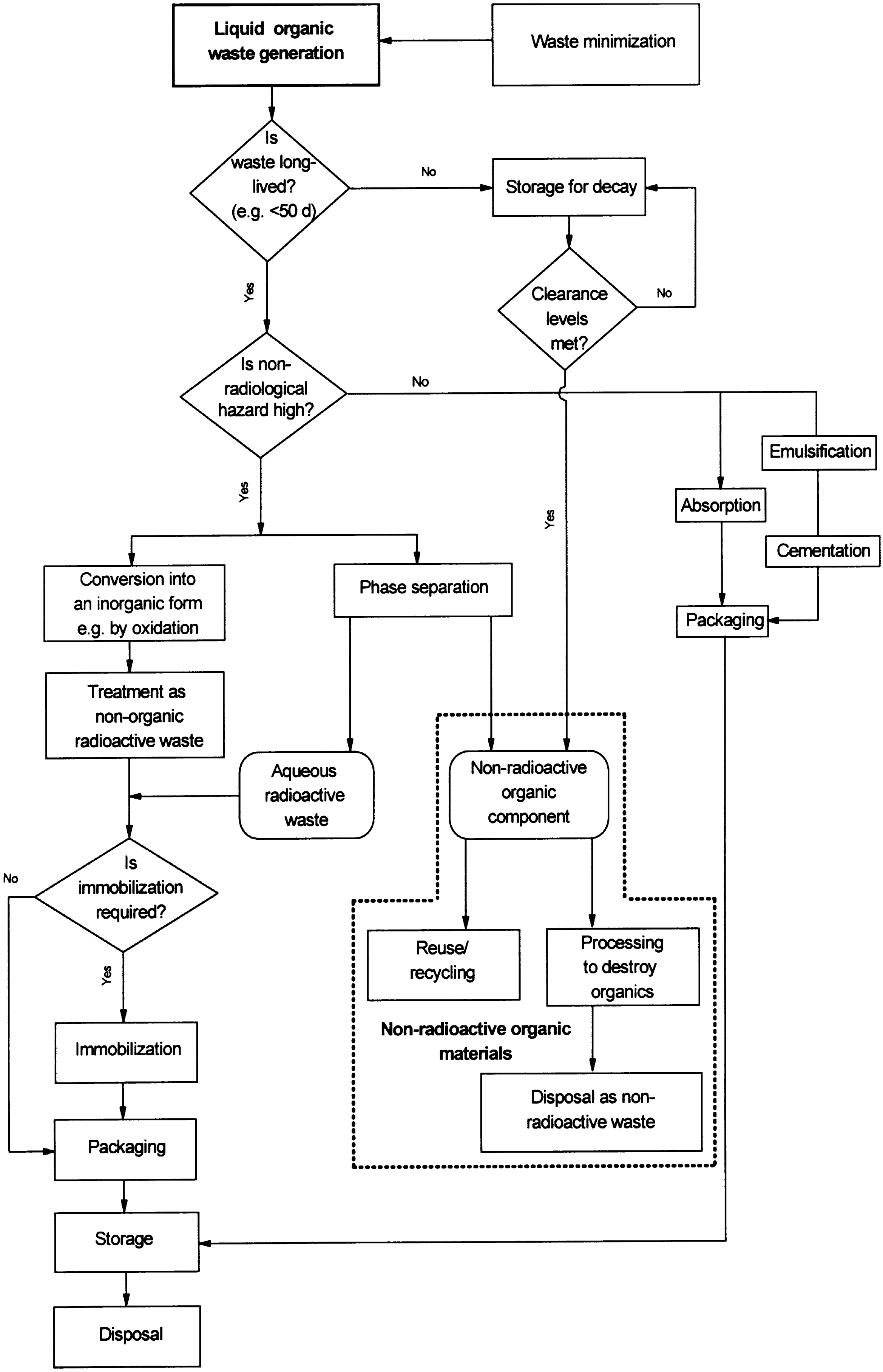

FIG. 7. Management flow diagram for liquid organic waste.

In many cases, processes selected for the treatment of aqueous waste can be adapted to the processing of organic liquid waste and combined processing could be cost effective. Where dedicated equipment for the destruction of organic liquid waste is desired, equipment cost, versatility for the treatment of a number of organic liquid waste, equipment availability, reliability in operation, and ease of maintenance are all factors to be considered in the selection of the process. Often, substantial advantages can be accrued by selecting a combination of two or more processes, rather than a single process.

A simple way of on-site treatment of organic liquid radioactive waste is converting the liquid to a solid form with absorbents. As long as there is an excess of absorbent there is no need even for mixing; the liquid waste can be added to the absorbent in a suitable container and eventually all the liquid will be taken up. This technique has been routinely used for the solidification of radioactive turbine and pump oil. The following main categories of absorbent are commonly used:

- Natural fiber (sawdust, cotton).
- Synthetic fiber (polypropylene).
- Vermiculite (mica).
- Clays.
- Diatomaceous earth.

The use of absorbents converts the liquid waste into a form which can vary from loose dry particles to a jelly-like solid. The waste forms have no special integrity and are only restrained from dispersing by the container. The absorption efficiency of the different absorbents can vary by a factor of 2 to 3, and the waste volume increase can be up to almost 300% [19].

The suitability of absorption alone for the solidification of organic liquid waste is only moderate; the process efficiency can be adversely affected by the presence of water or other ionic contaminants, and variations in waste viscosity can cause significant reductions in the quantity of liquid absorbed. The waste form is readily dispersible in air or water if the product container is breached. Finally, the oil released from these waste forms following the disintegration of the drums can directly affect the radionuclide retention prospectus of buffer and rock in a disposal facility. This may be important particularly when co-disposal of these waste forms with other radioactive waste is considered.

5.3.3. Solid waste

The essential purpose of solid waste treatment is to reduce 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. Available solid waste treatment options [20] include such methods as:

- Mechanical treatment (low force and high force compaction).

- Thermal treatment (incineration, thermal destruction, molten glass, molten salt, plasma arc incinerator, slagging kiln, plasma pyrolysis).

- Melting and sintering processes (metal melting, electroslag melting, plastic extrusion, microwave melting, plasma melting, ceramics production).

- Chemical (acid digestion, acid stripping, chemical oxidation, photolysis, electrolysis), biochemical and photo-oxidation decomposition.

TABLE VIII. MAIN FEATURES OF THE SOLID WASTE TREATMENT PROCESSES

Treatment methods	Features	Limitations
Low force compaction	• Relatively low cost. • Easy to operate.	• Low volume reduction factor (3–5).
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.
Incineration • Excess air • Controlled air • Pyrolysis • Fluidized bed • Slagging • Rotary kiln	• High volume reduction factor. • Low technology to high technology, matching the need of the user.	• Secondary waste resulting from incineration may require immobilization in high integrity matrix (e.g. cement). • Off-gas must be monitored and treated if required. • Trained workforce is required.
Molten glass/molten salt	• High integrity confinement. • Combines incineration and encapsulation features.	• Complex technology, with demanding workforce requirements. • High cost.
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.
Plasma arc incineration	• High temperature incineration.	• Advanced technology only suitable for advanced nuclear programmes.
Melting and sintering processes	• May facilitate decontamination and waste minimization. • Suitable for recycling and reuse.	• The volume of waste and technological needs of the country will have to be advanced. • Trained workforce is required. • High cost.
Chemical decomposition	• Avoids the necessity of high temperature incineration. • Suitable for biological waste.	• No volume reduction.

The waste concentrates having achieved the highest volume reduction are then routed to the appropriate conditioning step where the final package for interim storage or disposal is obtained.

Dealing with solid waste, the clearance from regulatory control applied to recycling, reuse outside nuclear facilities or disposal as normal waste is an important action to be taken. Such clearance can either be achieved by measurement and sorting, decontamination of contaminated waste materials; or by decay storage of waste contaminated with short-lived radioactive isotopes. At residual activity levels that would result in an individual dose, regardless of its origin, in order of some tens of microsieverts per year, that are likely to be regarded as trivial, materials can be recycled to unrestricted use or disposed of like conventional waste subject to efficient radiation measurements and monitoring.

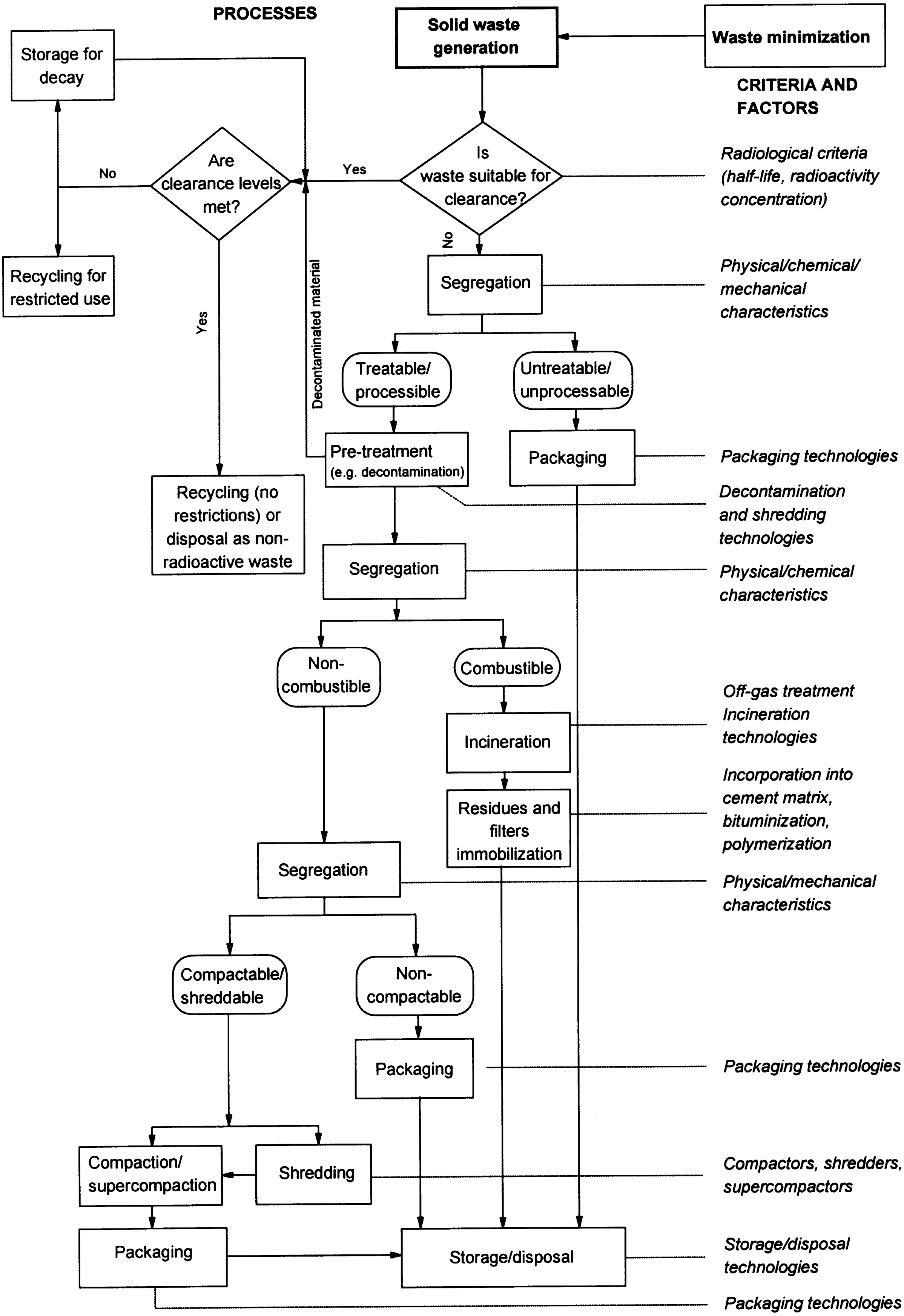

FIG. 8. Management flow diagram for solid waste.

Figure 8 is a flow sheet with a basic description of the management of solid radioactive waste. Table VIII addresses the main features and limitations of various forms of solid waste treatment. The figure and table may be used together to make some preliminary decisions about the technical feasibility/desirability of some options for managing low and intermediate level solid waste.

Incineration normally achieves the highest volume reduction and converts the waste to a form which is suitable for subsequent immobilization and disposal. However, incineration of solid waste, as in the case of organic liquid waste, should be considered only after careful evaluation of all features, especially radiological aspects. Incinerators without special air cleaning or ash-handling devices have a relatively low investment cost, but the activity of the waste incinerated needs to be restricted to levels which will not result in exposure of the general population to concentrations which exceed those permitted under national regulations or those approved by the Regulatory Body. Incineration of combustible waste containing larger quantities of radionuclides requires special off-gas cleaning and maintenance systems involving high investment and operation costs.

Compaction involves compressing the waste into containers or boxes in order to reduce the volume. Compaction is a suitable method for reducing the volume of solid waste. Different types and designs of relatively simple compactors with compressive forces between 10 and 50 tones are available offering varying volume reduction possibilities (typical volume reduction factor 2–5).

Shredding usually performed during pretreatment (including granulation, grinding, and pulping) breaks the waste down into smaller pieces. This process provides disfigurement of the waste and also prepares the waste for other types of treatment. The shredding process serves not only to disfigure the medical waste but to prepare it for distribution through the auger conveyor. Shredding may provide up to an 80% volume reduction.

Depending on the volume, nature and level of radioactivity, a suitable method could be chosen. For example, if the waste volumes and the activity levels are low, mere compaction and packaging may be sufficient before disposal. On the other hand, if higher volume reduction is desired, the appropriate technology may be supercompaction or incineration, followed by conditioning of the ash in a suitable matrix like cement. Such factors as the availability of disposal space in the repository, the nature of engineered barriers, the regulatory stipulations in respect of waste acceptance criteria for disposal and cost considerations would influence the choice of technology for conditioning.

5.3.4. Biological/Infectious waste

Biological waste (including biological tissue samples, carcasses, and excreta), if left untreated, will decompose and liquefy, and therefore increase the possibility to enter the biosphere. The goals of treatment of biological waste are the following:

- biologic detoxification;
- prevention of biological degradation;
- volume reduction.

A flow chart showing the steps in the treatment of biological (including infectious) radioactive waste is given in Fig. 9.

A new source of this waste involves the use of algae or bacteria to cleanse liquid or solid media of contamination, including radionuclides. Once these organisms have absorbed the contamination, they are harvested, immobilized, and disposed of. The least expensive method is to hold these samples for decay, if interim methods to prevent decomposition are available. If the contaminant has a half-life greater than e.g. 100 days, alternate methods of treatment, listed in Table IX are recommended [21].

Compaction and shredding, as described in Section 5.3.3., are not considered viable for treatment of biohazardous solid waste. The primary reason for this restriction is that any microorganisms contained within the waste may be spilled or released during these processes and contamination may be widely dispersed.

In cases where incineration is not available or the volumes of human and animal waste are so low that it is desirable to treat them on-site, it may be feasible to use maceration/pulverization to render these materials liquid, so that they can further treated as a liquid radioactive waste. This also includes any necessary chemical deactivation to treat the biological hazard.

5.3.5. Secondary waste

Pretreatment and treatment of radioactive waste usually generates secondary waste. This secondary waste may result from the 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, the secondary waste may be quite unique (e.g. incineration ash) and may require a different treatment.

TABLE IX. MAIN FEATURES OF BIOLOGICAL WASTE TREATMENT METHODS

Treatment method	Features	Limitations
Incineration	• Technique can be used to reduce the toxicity, mobility, and volume of several types of waste • Good, inexpensive, and effective. • Prevents putrefaction.	• Volume of waste generated must justify expenses.
Maceration/pulverization	• Change the physical form.	• Secondary waste must still be treated to remove or sorb liquids prior to disposal.
Chemical modification –mummification –desiccation	• Prevents decomposition and putrefaction. • Commonly practiced.	• Some toxic solutions may be required.
Freeze drying	• Removes liquids and leaves the solid waste for disposal	• Difficulties with large carcasses

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 the selection of the primary treatment process itself. Figure 10 is a flow sheet that summarizes the main features of secondary waste treatment. This figure also addresses the gaseous effluents (Section 5.3.6.) and the filters used to scrub gaseous releases as secondary waste.

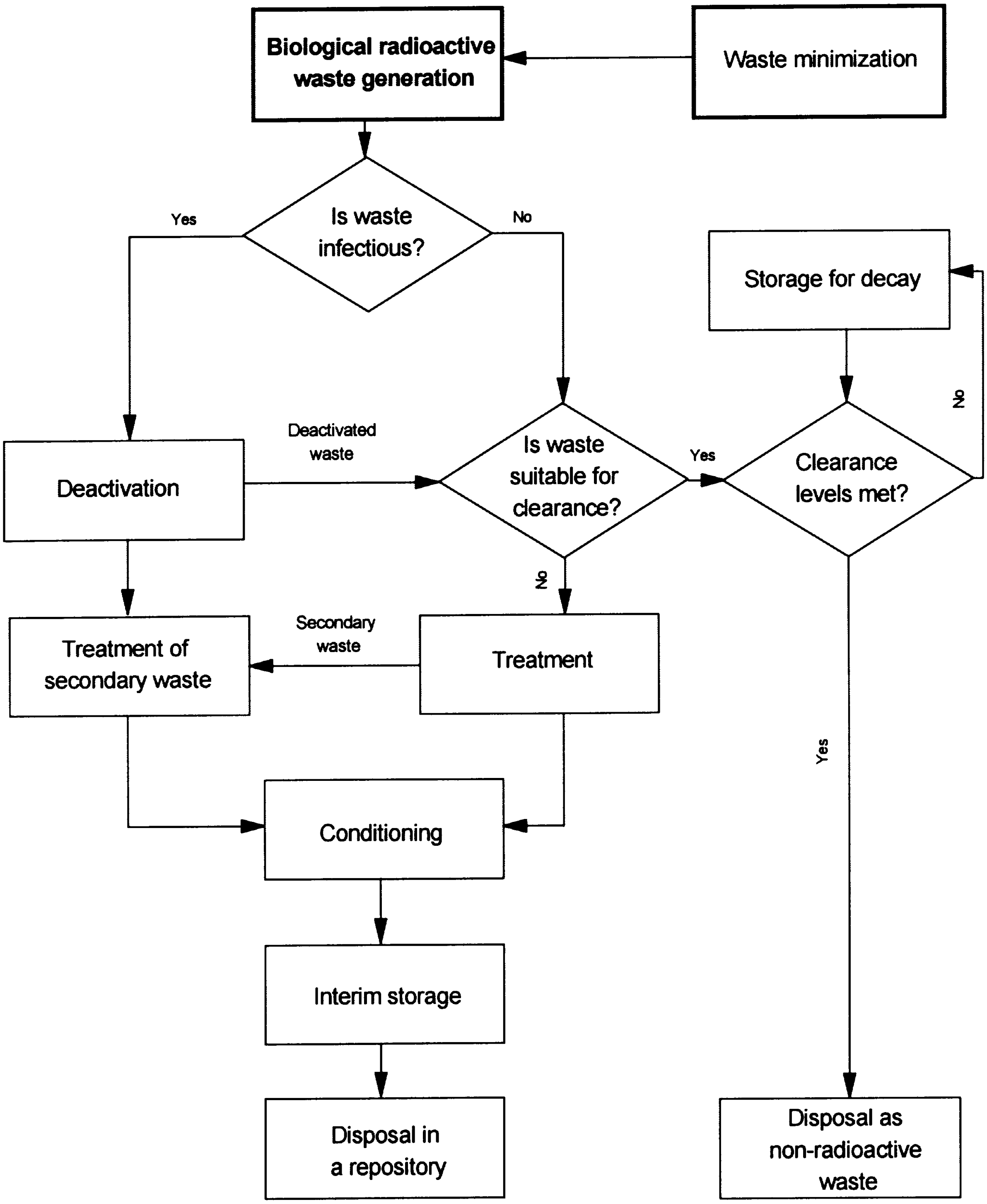

FIG. 9. Management flow diagram for biological/infectious waste.

5.3.6. Gaseous and airborne effluents

Any operation involving the handling of radioactive material may generate airborne radioactive contamination. The basic difference between airborne effluents and radioactive waste in condensed (i.e. liquid or solid) phase is that airborne material has no definite volume and its dispersion in the environment is very fast. Special technologies and equipment are therefore used for the localization, collection and treatment of airborne effluents [22]. Ventilation and air cleaning systems are a vital part of the general design of any nuclear facility. The combination of

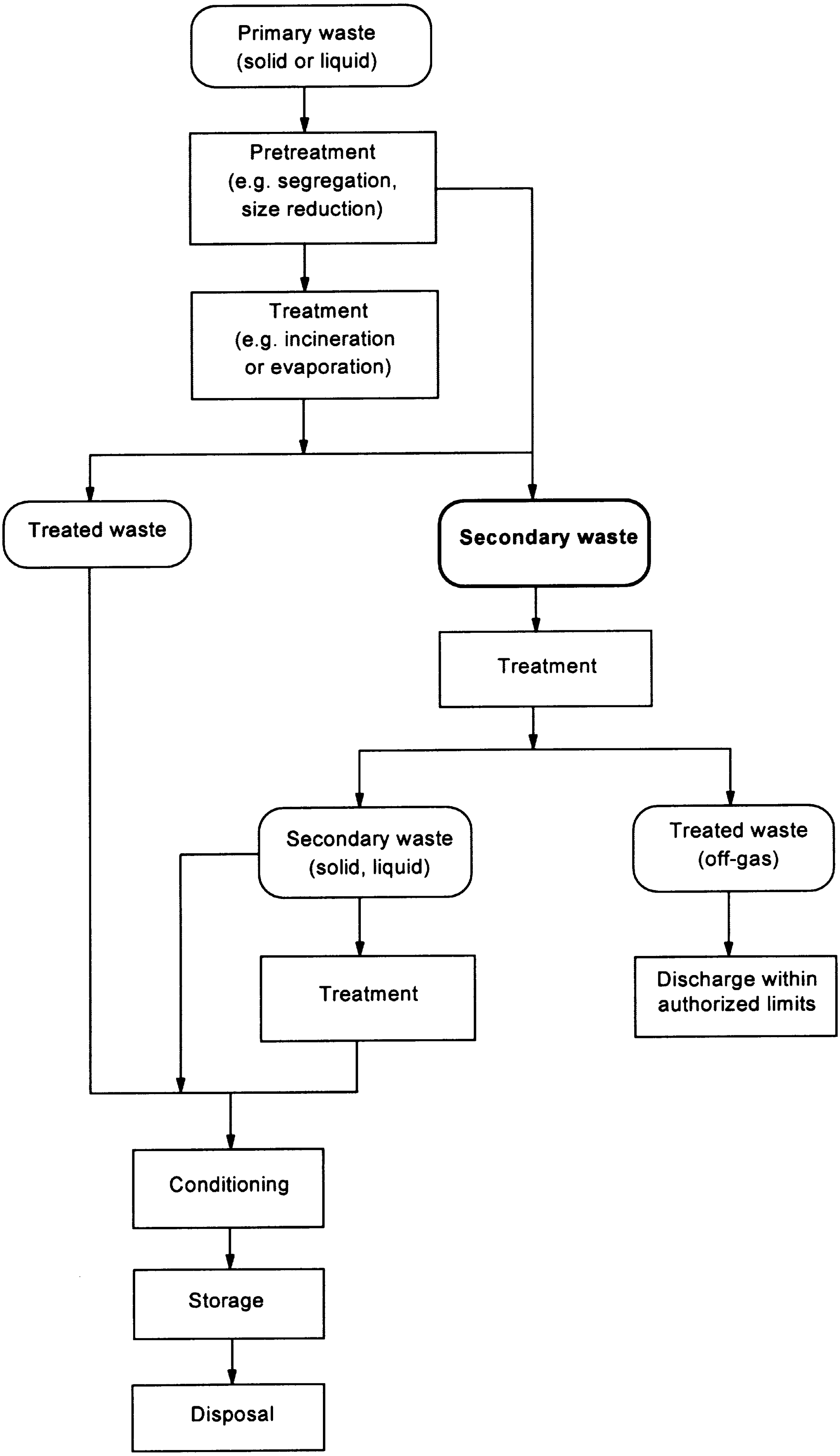

FIG. 10. Management flow diagram for secondary waste.

a well designed ventilation system with thorough cleaning of exhaust air prevents radioactive contamination of the air in working areas and in the surrounding atmosphere.

In nuclear facilities, in general, air streams from possibly high contaminated areas (e.g. hot cells, process vessels) are called off-gas streams. They may contain higher concentration of airborne radionuclides than the room ventilation air streams contaminated only from equipment or leakage from a hermetic area. Off-gas streams should therefore be treated prior to mixing with the ventilation air for occupational and environmental safety and economical reasons.

The general purposes of ventilation and air cleaning systems are:

- To control airborne contamination within the safe working levels.
- To filter and monitor the air supply on a once-through basis. This compensates for the air discharged to the atmosphere. Filtration of the inlet air is desirable to keep the dust concentration in the working areas to a minimum in order to reduce surface contamination and reduce the dust loading on the exhaust filters.
- To maintain directional flow from the point of least contamination to the point of greatest contamination. This protects the operators from the spread of contamination by a haphazard ventilation air pattern.
- To clean the exhaust air before discharge to the atmosphere. In order to determine the degree of cleanup required, a preliminary evaluation of the hazards of continuous normal release and the consequences of accidental releases is necessary. The discharge via an exhaust stack to ensure proper dilution may be required.
- To monitor contaminants in the working areas and releases to the environment.

In non-fuel-cycle facilities the ventilation and air cleaning system is usually designed to serve for both normal and accidental conditions, in nuclear power plants separate systems are established to minimize the consequences of accidental release.

Air inlet systems can be designed similarly to a conventional plant, containing fans, dampers, air conditioning devices and ducting. However, to increase the operation life of the more expensive high efficiency extract filters, reasonably high efficiency inlet filters are also required in the inlet systems.

An exhaust ventilation system is obviously a very important part of the plant. Exhaust air is filtered by **H**igh **E**fficiency **P**articulate **A**ir (HEPA) filters and — where appropriate — absorbers. Typical containment and ventilation system components include: fume hoods, fume cupboards, glove boxes, fans, and dampers.

5.4. CONDITIONING

Conditioning [23] is those operations that produce a waste package suitable for handling, transportation, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, waste immobilization 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 waste form may consist of raw solid waste, waste immobilized in glass, ceramics, cement, or bitumen and compacted pellets immobilized by grouting.

The *immobilization* of radioactive waste (solidification, embedding or encapsulation) to obtain a stable waste form may be an important step in waste management to minimize the potential for migration or dispersion of radionuclides into the environment during storage, handling, transportation and disposal. A number of matrices have been used to effect immobilization and include glasses, ceramics, cements, polymers and bitumens. 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. Many of the immobilization technologies and matrix materials are described in refs [24–27].

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 X indicates the relative merits of a number of the different matrices used for immobilization of low level and intermediate level radioactive waste.

TABLE X. GENERALIZED SUMMARY OF IMMOBILIZATION OPTIONS FOR LOW AND INTERMEDIATE LEVEL WASTE.

	Cement	**Polymer**	**Bitumen**
Process			
Complexity	Low	High/average	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-high	Low
Impact resistance	High	Average-high	Average
Fire resistance	High	Low-average	Low
Radiation stability	High	Average	Average
Retention of radionuclides			
* actinides	High	Low	Low
* short-lived	Low	High	High

Immobilization of low and intermediate level waste in *cement* has been practiced for many years. Processes for mixing the waste with cement can be divided into two categories: in-container and in-line. The advantages of using cement are:

- simple and low cost processing at low temperature;
- cementation is suitable for sludge, liquors, emulsified organic liquids and dry solids;
- waste forms demonstrate good thermal, chemical and physical stability;
- alkaline chemistry ensures low solubility for many key radionuclides;
- waste forms are non-flammable;
- high density of the waste forms provides good self-shielding;
- good compressive strength of the waste forms facilitates handling.

However, there are disadvantages of cement for the solidification of radioactive waste:

- some waste affect setting (e.g. lemon acid) or otherwise produce poor waste forms;
- pH adjustment or dewatering of waste may be necessary;

- swelling and cracking occur with some products when they are exposed to water or frozen;
- volume increase;
- excessive heat may develop during setting with certain combinations of cement and waste;
- dust problems may occur with some systems;
- equipment for powder feeding is difficult to maintain;
- potential maintenance problems may result from premature cement setting, especially in the case of in-line mixers.

Cement formulations have to be optimized to achieve a product of acceptable and consistent quality [25]. Typically, the cement is blended with Blast Furnace Slag (BFS) or Pulverized Fuel Ash (PFA) to limit the exotherm on hydration. Waste which react with the cement (e.g. aluminum or alumino-ferric flocs) may have to be limited in quantity per container or pre-treated. Waste which inhibits proper curing of the cement (e.g. waste containing oils or other organic compounds) may require some pretreatment to counteract their deleterious effects on the matrix, or may have to be carefully limited in terms of the amounts incorporated in the cement matrix.

Polymers such as polyester, vinylester or epoxy resins are usually limited to those applications where cement is unsuitable [26]. This is because they are considerably more expensive than cement and need a more complex processing plant. The principal advantage of polymers is their greater leach resistance for some radionuclides. However, the water content of the waste feed has to be carefully controlled and the polymers may, over long periods of time, degrade to form complexants which can increase the mobility of actinides.

There are about forty basic polymer families with commercial significance, and each family differs from all the others. Each polymer has a particular combination of properties, processing requirements and economic factors that make it ideally suited for specific types of waste yet unsuitable for many others [26].

The following considerations should be made in the selection of a polymer binder:

- long-term stability of the waste form produced;
- availability and cost;
- compatibility with a variety of waste;
- tolerance to waste stream variations;
- long-term stability of the waste forms produced;
- safety and ease of handling.

Pretreatment of waste before incorporation into the polymer matrix may be necessary to comply with the chemical requirements of the matrix material and to improve the quality of the product. Chemical pretreatment (pH adjustment, insolubility of salt waste and saturation of spent ion exchange resins) and/or dewatering of waste is generally practiced to improve its ability to be processed, packing efficiency and better product properties. Dewatering of waste can be accomplished by mechanical methods (e.g. by vacuum filtration or centrifuging), evaporation and evaporation/crystallization.

Drying of wet solid waste and liquid waste is required for solidification with certain polymers, such as polyethylene and ordinary polyester-styrene. The incorporation of dry waste into a polymer matrix results in high waste loading, and the problems associated with the presence of moisture or water are minimal.

Bitumen is used mainly for sludge, evaporator concentrates and ion exchange resins [27]. The heat of the bitumen conditioning process dries the waste, minimizing the water content and thus the waste volume. The characteristics of bitumen as matrix material for the incorporation of radioactive waste present the following advantages:

- insolubility in water;
- high resistance against diffusion in water;
- high chemical inertness, except oxidation;
- high biological inertness;
- high plasticity;
- good rheologic properties;
- good behavior towards aging;
- rather good stability against radiation;
- high incorporation capacity leading to good volume reduction factors;
- material abundantly available at a reasonable cost.

Nevertheless, as an organic material bitumen has the following disadvantages:

- tendency to swelling resulting in increased radionuclide release rates;
- decrease of viscosity as a function of temperature leading to a softening of the matrix that melts at temperatures >100°C;
- combustible, although not easily flammable;
- possibility of chemical interactions with certain components (e.g. nitrates, nitrites, etc.);
- low heat conductivity.

The various bituminization processes can be classified into batch processes and continuous processes. The choice when considering either a batch or continuous process depends on individual criteria such as the volume of waste to be treated, time restrictions, limited waste storage capacities, space availability and process economics [27].

If only dispersion of radionuclides during handling and transportation in case of mechanical and/or thermal incidents is of importance (e.g. for deep geological disposal) *high force compaction* may also reduce the potential for dispersion considerably.

A number of other promising stabilization techniques under development include *microwave melting, high pressure sintering, production of synthetic rock, and ceramization with or into natural clays*.

For high level waste the most common immobilization matrixes are glass and ceramic [28]. High level waste from reprocessing of spent fuel usually has the form of liquid concentrate and needs calcination as a first step to transform the solution in a solid waste form, which is transformed into insoluble, glass-like material suitable for very long-term storage and, ultimately, for disposal.

If reprocessing is not intended, spent fuel has to be disposed of as high level waste also and adequate treatment and conditioning [29] must be performed according to the requirements of the disposal site and, in addition, from handling storage and transport. To date, no country has directly disposed spent fuel. According to the reduced retention capability of spent fuel in comparison to the glass-like materials, the packaging are usually designed to contain the radionuclides for a specified period of time and to control the release of radionuclides after the containment period. Actual designs include outer packaging made from copper or titanium, or a resurting welding process for protection against corrosion.

Table XI indicates the merits of the different options for immobilization of these high level waste forms. The average retention of short lived radionuclides for spent fuel may require the application of outer packagings.

The *waste package* [23] is the product of conditioning 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, transportation, storage and/or disposal.

TABLE XI. GENERALIZED SUMMARY OF IMMOBILIZATION OPTIONS FOR HIGH LEVEL WASTE.

	Glass	**Ceramic**	**Spent Fuel**
Process			
Complexity	High	High	Average-high
Flexibility	Low	Average	Low
Volume reduction	Negative	Negative	Negative
Cost	High	High	High
Waste form			
Compatibility with waste streams	High	High	High
Waste loading	Average	Average	High
Compressive strength	High	High	Average
Impact resistance	High	High	Average-high
Fire resistance	High	High	High
Radiation stability	High	High	High
Retention of radionuclides			
* actinides	High	High	High-average
* short-lived	High	High	Average

Waste packages are designed to provide primary containment during interim storage, handling, transportation, and the operational phase of the repository and in some cases to retard release and migration of radionuclides and hazardous constituents in the long term (post-closure phase of the repository). The waste packages must be capable of meeting shielding and containment requirements for handling, storage, transportation and finally the waste disposal site requirements. The waste package prepared for disposal, when emplaced within a repository, must be assessed for its contribution in satisfying dispersal requirements. Factors of importance are:

- Limitations on activity content, surface dose rate and contamination.
- Protection against direct radiation, inhalation and ingestion hazards from radionuclides released during an accident causing by mechanical loads. This is a reflection of the containment offered by the mechanical properties of the container and waste form.
- Protection against the hazards from a fire, or any other credible release scenario, which reflects the thermal and chemical properties of the waste form.

The period of performance for the waste package begins at the time the waste form is produced and placed in the waste container, continues to the time the loaded waste container is configured with the other containers constituting the waste package, and extends through the end of the operation of the repository (i.e. through the time of disposal and into the repository post-closure period). In the post-closure period, the waste package will generally have two basic functions. Initially, the container itself may be necessary to limit the release of short-lived nuclides and to allow for decay to activities and temperatures which are acceptable for long-term analysis.

Secondly, after the container can no longer be considered to provide containment, the waste form should, if necessary, provide conditions to minimize the release of radionuclides and toxic materials into the near field. The importance of these two factors will vary according to the repository design. For instance, where the ground water return time is very slow the release rate may be less important; where it is short, they may be extremely important.

The *waste container* [23] is the vessel into which the waste form is placed for handling, transportation, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The container has a primary function to contain the waste during filling, storage, handling, transportation and emplacement in a repository thereby avoiding the formation of respirable fines. The container has to resist repository and possible impact pressures which will be non-uniform and which could be concentrated around the void spaces in the containment. Various container materials are used for waste packaging and they include mild carbon steel, stainless steel and concrete. For LILW forms, detailed descriptions of containers are given in Ref. [30].

The main functions of the waste package prepared for transportation are to avoid release of radioactivity from the waste form and excessive radiation levels outside the package. For the waste disposal package, the main functions of the outer container are to avoid mechanical damage to the waste container during repository operations or as a result of excessive expansions of the waste form, to prevent any contamination of the container during these operations, and to provide containment for a well-defined period in a final repository. In some cases overpacks may also contain buffer materials or absorbents intended to retard migration of waste constituents in the event of loss of primary confinement.

5.5. 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. While the storage of conditioned waste is normally described as interim storage, for some Member States this will probably be fairly long term even to the point of *de facto* disposal. Typically, between ten and fifty years will most likely be required for storage until a repository can be constructed and licensed.

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 any radiological hazards associated with radioactive waste. The design of storage facilities will have to meet the national regulatory standards and basic safety principles, as described in Section 3.2. The design proposed should follow these general principles and 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.

Storage requirements mandate external dose rate and contamination limits for waste packages to be accepted by the facility. In other respects the storage facility usually adheres to the waste acceptance requirements of the disposal facility. The storage facility should minimize radiation exposure to on-site personnel through appropriate siting and shielding.

In general, design criteria for storage facilities should take into account the following considerations [31]:

(a) Adequate segregated storage should be provided for untreated, treated, and/or conditioned radioactive waste with anticipation of future storage needs. These needs are, in turn, determined by the waste processing requirements and capabilities and the availability of specific treatment or disposal facilities, as well as package storage life and conditions. Untreated waste should be stored in a form and in a manner that limits the risk of dispersion.

(b) The storage facilities shall be designed to facilitate inspection and monitoring of stored waste as required. To the extent practical, retrieval of stored packages shall be facilitated by design to keep exposure to personnel as low as reasonably achievable (ALARA). Waste with short-lived radionuclides that is to be held for decay shall be segregated in a way that permits discharge as non radioactive waste when clearance levels are attained, as authorized by the Regulatory Body. The storage capacity of the facility shall be designed to accept the maximum operational holdings anticipated from the system. Waste not immobilized or conditioned shall be segregated according to its hazard level and, if possible, based on the type of repository.

(c) The storage capacity shall contain enough spare capacity to accept the content from another unit whose integrity may be breached or suspect. Appropriate facilities for transfer between operational and safety units shall be available.

(d) In the design of storage facilities for conditioned radioactive waste, consideration shall also be given to:

    (1) safe waste package handling;
    (2) clear identification of stored waste packages and record keeping;
    (3) surveillance of radioactive waste package integrity;
    (4) possible degradation of waste packages during storage;
    (5) provision of adequate environmental conditions (heating, cooling, humidity control) to ensure proper conservation of waste packages during their tenure at the facility;
    (6) provision for cooling for heat generating waste;
    (7) provision for fire protection where combustible waste is present;
    (8) provision for gas dissipation if gas generation is anticipated;
    (9) provisions for criticality control where fissile material is present in the waste;
    (10) prevention of unauthorized access; and
    (11) retrieval of the waste for disposal or in the event of an accident which requires relocation of the waste.

It is important that the storage facility 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 ground water. The storage facility should be sited away from other buildings in order to minimize radiation exposure to on-site personnel.

Waste storage which has been used or is currently in use, falls into three general categories:

(a) Sub-surface storage.
(b) Area storage.
(c) Engineered storage.

Sub-surface storage basically consists of emplacement of waste packages in engineered shallow trenches, frequently featuring a solid base of asphalt or concrete, with suitable backfilling material in such a manner that retrieval is straightforward. Sub-surface storage was commonly used in some Member States, notably the USA, to store large amounts of transuranic waste for periods in excess of 20 years. The cost of retrieval of this waste today, coupled with the risk involved, has demonstrated that this option is not a prudent one, if the design does not take cost and risk of retrieval into account.

Area storage, also referred to as open vault storage, consists of emplacement of waste packages on the ground or on a constructed base, either in the open air or with a simple open sided covering. Area storage may be considered for various waste packages such as mild steel drums with plastic liners inside containing pre-packed waste, ISO-freight containers containing drums or pre-packaged items, and plastic drums. Routine inspection of waste packages is, in many cases, a feature of such stores. The lack of climate control and potential exposure to the waste packages make this method of storage inadequate for long term storage of mild steel containers or drums.

Engineered storage refers to any fully contained building or structure specifically provided for the storage of waste packages. Engineered store designs are, in many cases, based on the need to handle large volumes of drummed or boxed waste packages with substantial surface dose rates. These stores may range from simply constructed enclosures to highly engineered facilities incorporating shielding structures and remote handling equipment, and fully serviced with ventilation, effluent collection, and instrumented controls. An engineered storage facility may be of simple construction, for example an inflatable building on an asphalt base pad. Alternatively a warehouse type construction with no arrangements for package handling, heating or ventilation is widely used. Recently more sophisticated engineered stores with full facilities have been constructed. The facilities may include arrangements for package handling, shielding with concrete (or equivalent), remote inspection, ventilation, temperature control, effluent collection, and prepared building surfaces to aid decontamination.

5.6. DISPOSAL

Disposal, as the final step in radioactive waste management, has been the subject of a number of R&D programmes, international studies and evaluations, reviews, and controversies between members of the public, scientists and decision makers. For the disposal of radioactive waste, two fundamental but contrasting courses of action are available:

- Isolation of the waste during a time adequate for the decay of the radionuclides to levels of insignificance.
- Dispersion and dilution of radionuclides into the environment.

The two courses of action are in fact necessary and complementary since it is just as impracticable to retain and contain all the radioactivity in the waste as it would be unacceptable to release all of it to the environment. At present, the internationally accepted disposal strategy is to contain most waste in repositories and take advantage of the isolation capability of geological environments.

Disposal can be totally irreversible, as for example in the case of release of effluents to the environment. Retrieval may be possible in shallow and subsurface ground disposal, as well as in some geological disposal schemes for solid waste, but disposal implies the absence of the intention to retrieve. Usually, disposal concepts do not require continued surveillance. However, in particular cases, such as shallow ground repositories, surveillance of the site during a limited period of time (referred to as the period of institutional control) may be part of the disposal concept. Furthermore, deep geological disposal facilities remain under surveillance at least until after sealing. In many cases, termination of surveillance will be a matter of special decision or even licensing. Management practices for the disposal of LILW include a number of options adopted or under consideration in different countries [32]. Such options are:

- Near surface disposal
  - shallow ground disposal
  - disposal in cavities at intermediate depth.
- Geological disposal.

The choice of a particular disposal system will depend on the waste type and local conditions, including considerations of socio-political acceptance. The availability of a disposal option may further influence the selection of a conditioned waste form and its packaging, since both have to be compatible with each other. The options are addressed below and summarized in Table XII.

5.6.1. Near surface disposal

The basic objective of near surface disposal is to isolate the waste from water and the human environment under controlled conditions and for a period of time long enough to allow the radioactivity to either decay naturally or slowly disperse to an acceptable level. This option implies that waste to be disposed of contains mainly short-lived radionuclides of low or medium specific activity with only low amounts of long-lived radionuclides and that a maximum authorized activity has to be fixed. Furthermore, the length of institutional control is an important consideration.

The oldest and simplest method of shallow land burial consists of placing untreated solid waste without engineered barriers, directly in excavated trenches and covering the waste with a layer of soil. Modifications have been made by improving the waste packages, back-filling voids between the containers with sand or other suitable earthen material, compacting the back-filled material, and covering the waste with a cover or cap of earthen material. In humid areas, the practice has typically been to locate trenches above the groundwater level and sometimes on a layer of low permeability material with good retention characteristics for most radionuclides present in the waste.

In the above concept, the primary protection is provided by the sorption properties of the overlying and surrounding soil. Erosion, intrusion by animals and deep root vegetation, and percolation of rainwater are the main processes adversely affecting this disposal option. It is generally recognized that this concept is best suited for disposal of very low level waste insoluble in soils with good sorption capabilities and in dry climate regions.

Shallow land burial facilities have undergone extensive evolution as a result of operational experience and requirements to improve radiological and environmental safety assurance of this disposal option. The improvements have resulted in increasing the number of engineered barriers to limit or delay radionuclide migration from the repository. In addition, experience has shown that waste not acceptable for disposal in a simple trench may be acceptable in a near surface repository with a multi-barrier system.

Typically, the disposal units are lined with concrete, bitumen or other material to improve isolation of waste. The space between the waste packages is often filled with soil, clay, or concrete grout. Low permeability covers are put above the disposal unit to minimize the percolation of surface water to the waste. Water diversion and drainage systems are used to direct water away from the disposal units. The system can further be protected from erosion by planting vegetation or covering surface with rock rubble.

The disposal units are usually located above the water table, however, in some countries, the local conditions require the disposal vaults to be constructed below the water table. The latter option calls for use of materials with low permeability to ensure low penetration of water into the disposal area and additional measures to control water infiltration, a matter of primary importance.

5.6.2. Disposal in cavities at intermediate depth

The primary distinguishing feature of cavity type repository as compared to shallow land burial concepts is that the distance below the land surface is adequate to essentially eliminate the concerns of intrusion by plants, animals and humans. The cavity type disposal concept has potential for a number of applications, e.g. different cavity types located at various depths in different geological environments can be used for different kinds of waste. In relation to their origin, the cavities may be classified into the following types:

- specially excavated cavities;
- unused mines;
- natural cavities.

It is not recommended to use such cavities for disposal without prior geological assessment. Specially excavated cavities for emplacement of waste can have various shapes and volumes which depend on the planned disposal method, the waste type and quantity, and the geometry of the host formation. The shape of the repository can include tunnels, bore holes, vertical or horizontal caverns, or some combination of these mined openings. Flexibility in positioning and shaping the repository is the major advantage of this disposal concept. The disadvantages of this concept may be their bad isolation from the biosphere, in particular direct connection to the groundwater, and the risk of water intrusion during the operational and/or post-operational phase. Cavity type repository concepts have been developed, in some cases, for more than one category of radioactive waste, e.g. long-lived LILW.

5.6.3. Geological disposal

Geological disposal is recommended for high level and long-lived waste. A geological repository should:

- be deep enough so as to protect the waste against involuntary or accidental intrusions and, in very unusual cases, voluntary intrusions (usually several hundreds of meters below the earth surface);

- be located in a host rock which is either dry or has a very slow groundwater flow;
- be compatible with the physical and chemical properties of the waste packages;
- be located in a seismically and geologically stable area;
- offer a geological barrier system against mobilization and migration of radionuclides, thus avoiding the need for engineered barriers or sophisticated waste immobilization;
- be such that waste will remain compatible with the properties of the host rock;
- offer, at least for the foreseeable future, no or very little economic value.

The length of time during which no release or acceptable releases of radionuclides from the waste in the repository can be assured, when considering periods well beyond 10,000 years, is the subject of a very difficult analysis, and results may have a high degree of uncertainty. However, it should also be recognized that the longer the period under consideration, the lower will be the residual amount of radioactivity.

The inherent effectiveness of such geological isolation systems may be enhanced by adding other barriers, e.g. the form of conditioning of the waste, overpack materials for the waste canisters, buffer and backfill materials and other engineered structures. Although the properties of the geological environment are usually the controlling factor in the long term safety of radioactive waste disposal schemes, the additional barriers can also play a role in the overall safety of the system.

5.7. MANAGEMENT OF SPENT SEALED RADIOACTIVE SOURCES

The safe management of spent radioactive sources includes the following activities:

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

The preferred practice is to return the source to a supplier or other organization for further use. Most new contracts for the purchase of sources contain a clause for the return of the sources once they are spent. 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 spent sources as the cost of packaging and transportation may be considerable.

In some countries, for example, it may not be possible to dispose of long-lived spent sealed sources because deep geological repositories are not available. In this case return to the suppliers or recycling (overseas) may be the best, if not the only, option. Encapsulation of spent sealed sources in an irretrievable form (e.g. by direct encapsulation in cement) will only serve to complicate future handling of the waste. Immobilization of waste in containers that are large or varied in size may have negative impacts on transportation, storage, or disposal if it is necessary to repackage the waste. It is much simpler to employ small packages of uniform size. If larger packages are required, then the variety of sizes should be limited to one or two types to facilitate economical use of space during storage and disposal.

TABLE XII. MAIN FEATURES OF VARIOUS DISPOSAL OPTIONS

Disposal option	Features	Limitations
Shallow land burial without engineered barriers	• Excavated trenches covered with a layer of soil • Simple and not expensive	• Suitable for short-lived and low level waste only • Erosion, intrusion and percolation of rainwater may affect the performance
Shallow land burial with engineered barriers	• Multi-barrier approach to enhance the safety of disposal • Suitable for most low and intermediate level waste • Long experience with operation	• Limited amount of long-lived waste to be disposed of in one facility • Erosion, intrusion and percolation of rainwater may affect the performance
Disposal in cavities at intermediate depth	• The depth is adequate to eliminate the risk of erosion, intrusion and percolation of rainwater • Flexibility in design Possibility to use existing disused cavities (e.g. mines)	• The geological barriers are site dependent • Extensive characterization of the site
Geological disposal	• Suitable for all waste categories • Enhanced confinement	• High cost • Complex technology involved • Assurance of site integrity for above 10,000 y • Extensive safety and performance analyses • Suitable geological media • Politically sensitive • No operational experience

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

- (if short-lived) transferred to an interim 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 interim store while awaiting eventual disposal. Conditioning can be carried out either on-site or at a specific conditioning facility. There are simple methods for conditioning of spent sources in a metallic drum filled with a cement grout. Large sources used for sterilization and irradiation should preferably always be sent back to the supplier. The recommended conditioning method for radium sources is encapsulation in welded stainless steel capsules and placing the capsules inside a metallic 200 L drum filled with concrete for shielding purposes.

A special problem exists with the disposal of spent sealed sources. Existing near surface repositories normally do not accept the conditioned spent 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.

The flow sheet in Fig. 11 depicts the steps that are required to disposition spent sealed sources. Ideally, all necessary manpower, equipment and facilities for safe management should exist within a country before a practice giving rise to spent radioactive sources is initiated.

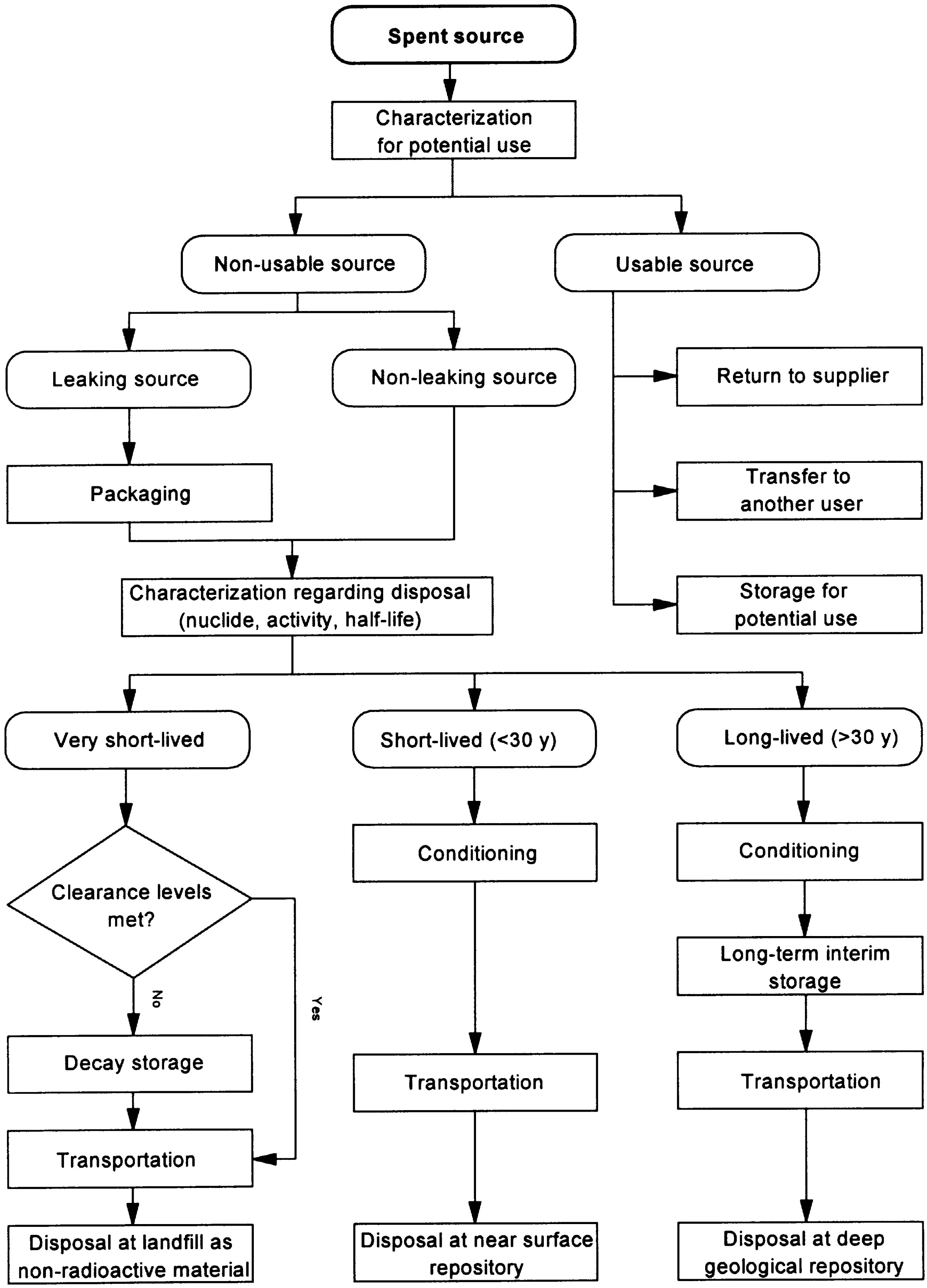

FIG.11. Management of spent sealed sources.

6. TRENDS IN WASTE MANAGEMENT

A number of trends in radioactive waste management in Member have been observed in recent years. They may influence the selection and application of waste management strategy and technology, and may represent important contributions for countries considering technological alternatives. These trends are summarized below.

6.1. LEGISLATION AND REGULATIONS

Since the beginning of the use of nuclear energy, however, more intensively during the last two decades, Member States establishing a framework of laws and regulations early in the process. This trend is especially prevalent, as one would expect, in the SIA and MIA countries. In addition, laws and regulations which already exist in RRA countries are being expanded to address new activities, such as waste clearance.

An additional requirement imposed on waste generators and operators of waste management facilities in some Member States is public involvement in the licensing process through e.g. "public hearings". The experience shows that such an involvement although increase the period of time needed for granting a licence, enhances significantly the acceptance of waste management activities.

6.2. WASTE MINIMIZATION

All Member States are actively exploring the benefits of waste reduction at source, waste segregation, and avoidance of waste contaminated with organic or other hazardous constituents. There is widespread knowledge that this mixed waste requires long-term isolation from the biosphere even after the radioactivity has decayed below clearance levels. As the cost of radioactive waste management continues to rise, this area will increase in importance. It is realized that the reduction of waste generation reduces the costs associated with its treatment, conditioning, storage, transport and disposal. Associated with the concept of segregation is the application of the clearance concept to very low level waste that can be managed after decay as non-radioactive waste. In this respect a trend to use shorter-lived radionuclides for the same applications that employed longer-lived radionuclides in the past should be encouraged. This trend has been made possible by the increased availability of short-lived radionuclides coupled with new research for application them in medicine.

New technology in the area of tracer studies allows the use of non-radioactive alternatives to radioactive tracers. Although the analytical equipment represents a significant capital cost, in the long run it may be less expensive than processing of resulting radioactive waste for disposal. In the new legislation of some countries there is a strong requirement that it must always be proved before introducing any use of nuclear energy that there are no other scientifically, technically and economically adequate non-nuclear methods to substitute nuclear methods.

Recycling and reuse of material from nuclear activities can reduce both the short and long-term impacts of waste generation. Spent sealed sources represent an issue for most Member States, yet arrangements can be made with the supplier to return the discarded spent source. A centralized source registry in the country can catalogue and redistribute sources from where they are not in use to where they are needed, as an alternative to the purchase of new sources for every new practice.

6.3. QUALITY ASSURANCE

An increased implementation of quality assurance and understanding its role in waste management is helping, especially SIA, MIA and RRA countries to build better facilities and to manage their waste streams in a more efficient way. It was noted that waste packages produced by processes governed by quality assurance programmes do not require reconditioning, and also experience with waste packages in extended storage is good. This translates directly into enhanced safety and efficiency for Member States.

6.4. LONG-TERM STORAGE OF WASTE

There is a trend in many Member States to postpone disposal in favor of long term storage. This option has been made possible by the institution of strict quality assurance measures that assure the performance of a waste package in storage for longer periods of time. The construction of long-term storage facilities that are well matched to the waste packages stored, there has also enabled this option to be exercised.

At some point, for low and intermediate level waste, deferred disposal becomes *de facto* disposal. Member States should realize the economic and social cost, risk(s), and benefits associated with this institutional delay. Some countries do not have a real choice regarding waste disposal. No deep underground disposal facility is available, and one is not likely to become available for 50 years or more. In this case proper storage and surveillance is only method available for safe confinement of radioactive waste.

6.5. COMMUNICATION AND SOCIO-POLITICAL CONCERNS

Many countries will not have the waste volume sufficient to justify the construction of a unique set of waste management facilities. Regional groups are considering the development of compacts that feature waste processing, storage, and even disposal facilities on a cost share basis. However, in case of disposal the legislation in some countries forbids disposal of waste arising in foreign countries. Siting of these facilities and cost burdens are major stumbling blocks to progress in the area of regional compacts. The question is raised of how the cost should be shared. It can be based on waste volume, relative Gross National Product (GNP), or ability to pay. It depends whether the host country is willing to have payment deferred? Such questions are all non-technical, however, they bear the greatest impact of any factor in the waste management process. Increased communication could benefit Member States because it enhances understanding, reduces suspicion of motives, fosters technology transfer, and increases the opportunity for solving common problems.

There is also a trend toward the increased use of safety and risk assessment physical protection and safeguards measures in the design and operation of waste management facilities, especially when those facilities are used for more complex tasks or new tasks not anticipated in their original design.

6.6. TECHNOLOGICAL TRENDS

Member States with developing nuclear programmes are learning the lessons of more experienced countries through the trend of engineered flexibility in the design of their facilities.

This trend allows them to expand or reduce floor area committed to nuclear development. It also may allow them to develop nuclear technology for export to other countries as a method of return on the investment made in their own nation's nuclear future.

Major efforts have been spent worldwide to develop new methods for treatment and conditioning of radioactive waste. There are several motivations behind these efforts:

- cost reduction,
- improved efficiency (volume reduction, characteristics of final waste form, etc.),
- environmental impact of some current technologies,
- reactions of stakeholders.

The information given below represents some developments of new or emerging processes; some of them may be really promising in specific circumstances. However, their routine application might still belong to organizations which are closely linked to R&D institutes.

6.6.1. Mobile facilities

Some Member States have resorted to mobile processing facilities that take the equipment to the waste generator and process it on-site for further storage. This is a development that would benefit numerous small users in an area or a region. If one Member State developed the technology, other near located states would only have to provide the waste for on-site processing, followed by on-site storage. This is another way that Member States can realize a return on their investment in equipment and manpower training. A typical example is the use of mobile supercompactors.

6.6.2. High temperature technologies

(a) Vitrification

Given the good results obtained with vitrification of acid and neutralized high level waste from reprocessing, several projects are underway for the vitrification of slurries, low- and intermediate level solid waste, mixed waste, etc. The expected advantages are: volume reduction, destruction of organic constituents including hazardous materials, immobilization of radioactive and mineral hazardous components, advantages for disposal. Large scale demonstration projects are already being performed or planned. Technical variants of vitrification relate to the mode of heating (joule, plasma, gas, etc.), shape of the furnace and pretreatment of the raw materials, e.g. segregation, grinding, homogenization, incineration. In order to simplify the application of such processes, the latter should be "robust", which ideally would mean that they accept almost any waste after a minimum of up-front characterization, with reproducible characteristics of the end-product and acceptable off-gasses. Apparently, there is no basic reason why such objective could not be reached, in a satisfactory way.

Once sufficient demonstration experiments will have been performed with real radioactive waste, the technology seems promising essentially for its numerous potential advantages and for mixtures of solid- and semi-solid waste. Vitrification should not be considered for cases where the radioactive contaminants are essentially volatile or semi-volatile. For Cs-nuclides this problem should be technically solved in the design of furnace. One technical variant consists of a transportable facility. The technology can be considered for throughputs of a few tens of kg per hour to several hundreds of kg per hour.

(b) Fixation of high level wastes into ceramic materials

New promising ceramic materials and methods of fixation (like SYNROC) were developed or are in the stage of developing. Ceramic products are crystalline in nature and therefore thermodynamically stable. They are expected to be more stable in the underground environment and have a high potential for incorporating alpha-bearing waste like plutonium.

6.6.3. Low temperature technologies

(a) Replacement of incineration by supercompaction

There is a noticeable trend away from incineration to supercompaction. This is likely due to the necessity, with incineration, of immobilizing the intermediate activity secondary waste (ash) and treating the off-gas. In addition, the gaseous effluents may be viewed as a problem to neighboring Member States, and this may represent a situation desirable to avoid. Also monitoring of effluents can cause many problems which are difficult to solve. Supercompactors are not without their technical challenges. These machines compress waste at very high pressure loading, and are subject to breakdowns and very high maintenance. Effluents must be filtered, but the unit is self-contained for that purpose. As a whole, this method generates less secondary waste, however the volume reduction factor is usually much lower (depending on the initial waste form) than incineration.

(b) Cementation (grouting)

There is continuous R&D on the improvement of the process of grouting of LILW with the aim to increase the capacity for encapsulation of specific constituents such as salts, organic solvents and ion exchangers, and to improve properties of the cemented waste forms.

The range of applicability of grouting is to be considered in view of the characteristics of the environment and of the initial waste. The cement may display pH buffering properties and, consequently, control mobility of some radionuclides in the disposal environment. The problematic side is the relatively high porosity and leachability for some radionuclides of the end-product and, in general, resulting volume increase rather than decrease.

Two technical variants of grouting are currently being considered with the primary objective to improve long-term stability and control of the leach rate:

- sulfur cement,
- phosphate bonded ceramic.

Both are typically low temperature processes. Their advantages are the reduced solubility/leach rate in the environment and their application for radioactive waste containing hazardous metals (Hg, Pb, Cd, As) in the form of salts or pure metal. They also seem to be efficient for the immobilization of alpha-bearing waste.

(c) Non-thermal oxidation

As a kind of pretreatment, non-thermal oxidation systems can be used to eliminate organic constituents in particular specific organic constituents. These methods are based on electrochemical or catalytic oxidation, oxidation by strong chemical oxidants, such as peroxides, persulfates and/or supercritical fluids. These approaches are still in the R&D or demonstration phase. Best and reliable results are obtained for specific organic materials, such as diluted solvents and/or ion exchangers. In general, the end-products require a form of secondary immobilization.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Balu, K.	Bhabha Atomic Research Centre, India
Chan-Sands, C.	International Atomic Energy Agency
Dormuth, K.	Atomic Energy of Canada Ltd, Canada
Holmes, B.	British Nuclear Fuel plc., United Kingdom
Holub, J.	Agency for Radioactive Waste (ARAO), Czech Republic
Malik, S.A.	Malaysian Institute for Nuclear Technology Research, Malaysia
Martens, B.R.,	Bundesamt fuer Strahlenschutz (BfS), Germany
Roberts, P.	AEA Technology, United Kingdom
Robbins, R.	British Nuclear Fuel plc., United Kingdom
Stupka, R.	Los Alamos National Laboratory, United States of America
Tsyplenkov, V.S.	International Atomic Energy Agency
Valdezco, E.M.	Philippine Nuclear Research Institute, Philippines
Zhu, J.-L.	China National Nuclear Corporation, China

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