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CHARACTERISTICS OF RADIOACTIVE WASTE FORMS CONDITIONED FOR STORAGE AND DISPOSAL: Guidance for the Development of Waste Acceptance Criteria

REPORT BY AN ADVISORY GROUP MEETING ON CONDITIONING REQUIREMENTS FOR STORAGE AND DISPOSAL OF RADIOACTIVE WASTES ORGANIZED BY THE INTERNATIONAL ATOMIC ENERGY AGENCY AND HELD IN VIENNA, 23–27 AUGUST 1982



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FOREWORD

This report is addressed to specialists responsible for or involved in the development of waste acceptance criteria for the underground disposal of radioactive wastes as well as those for conditioning wastes for disposal. It presents data and other information, based on the conditioner's experience and viewpoints, which are relevant to the formulation of waste acceptance criteria. It is believed that consideration of both the conditioning and the repository aspects at the same time will enhance the development of practical criteria that can be met and will be acceptable to conditioning, repository operators and regulatory authorities.

The IAEA has been active in the field of radioactive waste management for many years. Frequently the Agency has held symposia including aspects of the conditioning of high-, intermediate- and low-level wastes, many of them in cooperation with the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA) and/or the Commission of the European Communities (CEC). IAEA and OECD/NEA symposia held in 1965 and 1970 dealt exclusively with the treatment, conditioning and management of low- and intermediate-level Immobilization techniques for all types of liquid and wastes. solid wastes from the nuclear fuel cycle were discussed in international symposia in 1972 (OECD/NEA and IAEA), 1976 (IAEA and OECD/NEA), and 1980 (IAEA and CEC). In addition, an IAEA/CEC/OECD-NEA symposium specifically on conditioning was held in 1982. The Agency has also had an Advisory Group and a Coordinated Research Programme, respectively, on techniques for the solidification of high-level wastes and evaluation of solidified high-level waste products. A Technical Committee also prepared a technical report on conditioning of low- and intermediate-level radioactive wastes. Technical information from these latter activities, in particular, provide much of the basis for the content of this report.

This report was drafted by two experts,* at a consultants meeting in Vienna from 7 to 11 September 1981, and subsequently revised by them with E.R. Irish as reponsible officer from the IAEA. It was reviewed and revised by an Advisory Group meeting held in Vienna from 23 to 27 August 1982. The Scientific Secretary of the meeting was V. Tsyplenkov of the Waste Management Section who was responsible for the completion of the report. The report prepared in conjunction with the Agency's underground disposal programme is expected to provide useful information for the formulation of waste acceptance criteria.

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1 INTRODUCTION

Radioactive materials that are no longer useful become wastes that must be isolated from the human environment during storage and after disposal as long as potentially harmful levels of radioactivity exist. The level of radioactivity of these wastes reduces with time as a result of decay, at rates depending upon the half-lives of the specific radionuclides and their daughter products. For most radionuclides of importance in waste storage and disposal, the half-lives vary from about one year to thousands of years or more. Thus, radiological safety measures are needed for long time periods.

Radioactive wastes can be categorized in many ways based on one or more of their characteristics, e.g. their concentrations, activities, toxicities, physical forms, as well as the half-lives of the radionuclides involved. For the purpose of this report, wastes are grouped into five categories [1]:

- I. High-level, long-lived
- II. Intermediate-level, long-lived
- III. Low-level, long-lived
 - IV. Intermediate-level, short-lived
 - V. Low-level, short-lived

The levels of activity refer to the beta-gamma radiation levels and are most relevant to the heat removal and shielding requirements. Long-lived wastes contain significant amounts of alpha-emitting radionuclides, whereas the short-lived wastes have insignificant amounts.*

The types of waste management facilities used for storage, transport and disposal of wastes for the above categories vary. Similarly, the types of conditioning (i.e. immobilization and packaging) are different. For example, high-level wastes may be incorporated into a leach-resistant borosilicate glass, intermediate-level wastes and some low-level wastes may be incorporated into cement, bitumen or polymers and other very low-level wastes may simply be packaged in plastic bags or metal drums. Moreover, the requirements of waste conditioning may vary, e.g. it may be more stringent for storage and transport than for disposal, but it must be compatible with the overall disposal system. The presence of significant alpha-emitting radionuclides and type of conditioning used generally governs the assessment and choice of disposal repository.

Disposal of radioactive wastes in underground repositories, well designed and sited, is considered a safe

^{* &}quot;Insignificant' indicates that the amount is not important for a particular waste package and disposal situation, based on results of safety analysis.

method for properly conditioned wastes [1]. It is generally agreed that high-level and alpha-bearing (long-lived) wastes be emplaced in mined repositories in deep geological formations.Short-lived, intermediate- and low-level wastes may also be emplaced in deep repositories, but for economic reasons disposal in shallow ground repositories or mined cavities is generally preferred. Under the terms of the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter [2], some countries also dispose of packaged low-level solid wastes in the deep ocean. (Conditioning of low-level wastes for sea dumping is outside the scope of this report, though contained herein, hence it may as well be applicable to sea dumping. Packaging of waste for sea disposal is covered by [13].)

The effective and safe isolation of radioactive waste depends on the performance of the overall waste disposal system. This system consists of the immobilized waste form in a suitable container (the waste package), any engineered barriers within the repository and the natural barriers of the site (i.e. the host rock and the surrounding geological media). Together as a total system, these components must be selected and designed to provide the isolation required to protect the human environment.

In establishing the criteria for acceptance of conditioned radioactive wastes for disposal, regulatory authorities need to use the results from safety assessments of disposal systems. They also need to know what might be achievable and what would be practical criteria. For example, how much waste can be accommodated in a particular matrix material; how durable is the resultant waste form; is the waste form stable to the radiation dose it will receive, etc.?

In general, the conditioner of wastes can immobilize them in various forms and package these waste forms in containers made of various materials. Methods for doing these operations have been reviewed elsewhere [3-8]. Moreover, the waste producer and conditioner will wish to be satisfied that his conditioning activities are cost effective and will enable the transfer of the packaged waste to the waste repository operator.

The interplay between the activities of the waste producer and conditioner on the one hand and the waste repository operator and regulatory authority on the other needs to be integrated into the analysis of the total system, which will be site specific.

Analyses of total systems are currently limited, since few examples of actual waste repositories exist. However, studies are underway to develop and integrate the various aspects of the analyses [9-11]. Waste acceptance criteria are aspects of the system that are especially important to the waste producer and conditioner. Criteria for high-level wastes, in particular, are being developed from a repository perspective, but are now only in a qualitative stage [10]. Thus, it is important that the ranges of conditioning options and specifications which might be achieved in a realistic situation be understood and considered by all participants in these studies.

The purposes of this report are: (a) to provide a perspective on how waste conditioning can be responsive to waste acceptance criteria, and, (b) to discuss considerations, from a conditioner's viewpoint, regarding practical waste acceptance criteria, based on such questions as:

- How much conditioning can be accomplished using available technology?
- How can the waste forms and packages be expected to perform in storage, transport and disposal situations?
- What can be done to assure their quality?
- What are the economic implications of the various conditioning methods?

By considering potential waste conditioning options and specifications concurrently with the development of waste acceptance criteria, it is believed that the interplay between the two activities will result in practical criteria that can be met and will be acceptable to the conditioner, the repository operator and the regulatory authority.

2. SCOPE

This report briefly refers to various waste conditioning methods, and discusses considerations, from a conditioner's viewpoint, regarding practical waste acceptance criteria for high-level wastes and/or low- and intermediate-level wastes as functions of a series of specific characteristics, which will be described in Chapter 3.

2.1 High-level wastes

These wastes arise from the chemical reprocessing of irradiated fuel (aqueous waste from the first solvent extraction cycle and those waste streams combined with it) and contain mainly fission products as well as some actinides. If the reprocessing option is not to be adopted, spent fuel must also be considered as a waste and numerous aspects of the text will be relevant to it.

Conditioning methods to convert high-level wastes to an immobilized waste form in a suitable container have been described elsewhere [5]. These wastes will then be stored for extended periods [12] prior to their eventual emplacement in a waste repository, as outlined in [1].

The contents of this report as mentioned earlier are intended to support the development of practical waste acceptance criteria which will eventually lead to waste package specifications. Until such time as an actual site for a waste repository has been identified, so that detailed site-specific safety analyses can be performed, absolute specifications cannot be written for the waste disposal package, i.e. immobilized waste form and container(s).

2.2 Low- and intermediate-level wastes

These wastes arise from many parts of the nuclear fuel cycle in relatively large volumes and in a variety of forms. A procedure similar to that used for high-level wastes is adopted for discussing the conditioning of low- and intermediate-level wastes, recognising, as described in [8], that the wastes themselves are more diverse in nature than high-level wastes and the conditioning options are much greater. However, many of the characteristics are generally relevant. For example, low- and intermediate-level wastes which contain appreciable levels of alpha-emitting radionuclides have to be considered in a way similar to that for high-level wastes, apart from the initial period of heat generation which is characteristic of high-level wastes. In addition, for those countries without major nuclear power programmes, there may be low-level wastes arising from research facilities, medical applications, etc.

Since the disposal of short-lived low- and intermediate-level wastes in shallow ground and mined cavity

repositories is practised in numerous countries, the contents of this report are intended to support the development of improved waste acceptance criteria and waste package specifications. With the relatively large volumes of these wastes, the balance between the cost of conditioning and the cost of disposal is one aspect that may be more significant for these wastes than for high-level wastes and a principal motivation for improvement.

A practical approach would recognize the fact that conditioning requirements often are related to the extended storage of these wastes due to the delays in disposal programmes.

2.3 Approach

This report attempts to review the characteristics* of the individual components of the waste package, i.e. the waste form and the container, in order to formulate, where appropriate, guidelines for the development of practical waste acceptance criteria. Primarily the criteria for disposal are considered, but if more stringent criteria are expected to be necessary for storage or transportation prior to the disposal, these will be discussed. (Regulations for the transport of radioactive waste are already published [14].) The report will also suggest test areas which will aid the development of the final waste acceptance criteria.

^{*} In several instances, both properties and characteristics are described; for simplification these are referred to as characteristics in this report.

3. OBJECTIVES OF CONDITIONING FOR STORAGE AND DISPOSAL

The intent of waste conditioning is to immobilize and package wastes so that they are suitable for all stages of handling, storage and disposal. This objective is met when the conditioning provides for:

- safe handling during predisposal and disposal operations (i.e. storage, transport, emplacement in the disposal facility); there should be no release of radioactivity from the package under normal conditions and releases under accident conditions need to be acceptable to the regulatory authorities;
- restricting the release of radionuclides in such a way that their concentration remains low. The limit should be based on an overall safety analysis of the total system and not just the performance of the waste package.

It is now generally accepted that disposal systems will consist of a series of barriers, each designed to prevent, delay or restrict the release of radionuclides from the waste and/or repository into its surroundings. These barriers can include:

a) Natural barriers

The geological formation in which the repository is sited and the surrounding geological environment. These should restrict the access of groundwater, and retard the movement of released radionuclides along the possible pathways from the repository to the biosphere.

b) Engineered or man-made barriers

Physico-chemical form of the waste (low leachability and low dispersibility)

Container(s)

Additional engineered barriers in the repository, such as secondary containers and geochemical barriers, (e.g. backfill materials).

It should be noted that for shallow ground disposal reliance may have to be placed primarily on engineered barriers, on limiting the quantities of waste emplaced in a repository, and on other institutional controls, rather than on natural barriers and a remote location of the disposal facilities.

In general, safe underground disposal of radioactive wastes is achieved by a combination of:

 a) Confinement of the waste in one or more natural or engineered barriers and thus its adequate isolation from the human environment.

- Retardation of radionuclide migration if the waste is, or will be, in contact with the groundwater or subject to other migration mechanisms.
- c) Disposal of the waste at a depth and location (especially for high-level and alpha-bearing wastes) where future natural or man-made disruptive events are extremely unlikely.

The most essential characteristics of an underground waste repository are the appropriate design of the selected repository facility and its location in a geologically stable environment with favourable hydrogeological characteristics such that the wastes, once emplaced, will be isolated from the human environment for the required period of time. The characteristics of the disposal site, its location and the design of the disposal facilities will determine the type, quantity and the extent of the conditioning of the wastes to be emplaced.

3.1 Development of criteria

In the process of developing criteria, a hierarchy of criteria must be defined before detailed "waste acceptance criteria" can be properly considered. At the present time this hierarchy appears to have the following sequence:

- Basic health and safety criteria. (Criteria established by national regulatory authorities, based on ICRP recommendations and other international and national guidelines.)
- General criteria for waste storage and disposal. (Generic criteria addressing the entire storage and/or disposal system in the context of the site, the storage facility and/or disposal repository and waste package.)
- Site-specific criteria. (Same type as the general criteria but applied to a specific site.)
- Technical criteria and economic considerations.
 (Assessment of the technical feasibility of the various conditioning options and their costs.)

Fig. 1 shows schematically how generic or site-specific waste acceptance criteria may be derived. This report is intended primarily to define and discuss the technical feasibility and characteristics of the various conditioning options available for packages of waste from the nuclear fuel cycle eventually to be emplaced in waste disposal repositories. The safety and economic analyses required to select a preferred conditioning option(s) are parts of the subsequent process of establishing practical waste acceptance criteria.



FIG. 1. Derivation of generic or site-specific waste acceptance criteria

3.2 Quality assurance

An overall quality assurance programme for all aspects of the waste package should be established. It should clearly delineate the responsibility and authority of the various personnel and organizations involved and define the organizational structure within which the activities are to be planned.

3.3 Functional waste package criteria

As mentioned previously, quantitative waste acceptance criteria have not yet been generally proposed, although such criteria have been defined for low- and intermediate-level alpha-bearing wastes for the Waste Isolation Pilot Plant in the United States [11]. However, "functional" criteria have been proposed for the waste package at the generic repository system level [9,10]. In these functional criteria the requirements of the waste package are defined.

For purposes of this report, functional criteria for the waste package are divided into three groups covering various periods of the waste package lifetime:

- Handling and identification
- Operational period
- Post-sealing period

The requirements included in each group are listed below:

3.3.1 <u>Handling and identification</u> – The waste package shall be designed to facilitate handling and identification through the operational period.

- a) The waste package and overpack shall be standardized by waste type to the extent practical.
- b) Each waste container shall be uniquely identifiable in a permanent manner.
- c) Permanent records shall be maintained for each waste package.

3.3.2 <u>Operational period</u> - The waste package shall provide protection against the release of radioactive materials for all reasonably expected conditions associated with the package, transportation and the storage facility and repository operating phases, and it shall be designed to protect against interactions with other packages or storage facility and repository components that could adversely affect containment. (Basic health and safety criteria for normal operations require that human exposures should not exceed the appropriate limits and should be as low as reasonably achievable.)

- a) The waste container shall remain intact throughout the processes up to the sealing of the repository.
- D) Analysis of the limits of release shall consider chemical reactions, corrosion, biodegradation, gas generation, thermal effects, mechanical effects, radiolysis, radiation damage, radionuclide mobility and other credible interactions. To limit release, waste forms shall be solids, resistant to dispersal in air or water and which do not contain sufficient free liquid to cause or provide a significant source of contamination.
- c) The surface dose rate and contamination of the waste package shall be commensurate with approved handling procedures. Furthermore, the waste package shall restrict radionuclide release in the event of a credible handling accident. The package shall be capable of withstanding credible impacts and free drops of equipment. In particular, if breached, the package shall restrict the release of particulate and gaseous material.
- d) The waste package shall satisfy the IAEA Regulations for the Safe Transport of Radioactive Materials [14]. Accident situations are covered by the regulations.
- e) The waste package should not sustain combustion or contain explosive, phyrophoric or chemically toxic or corrosive materials that could compromise safety. In specific cases, if such materials are present, special considerations must be given.
- f) Waste packages shall not generate gases in quantities or pressures sufficient to degrade performance.
- g) The content of fissile elements in the waste package must be limited to prevent criticality during all aspects of the handling in the operational period.

3.3.3 <u>Post-sealing period</u> - Following containment failure, the release from the waste package when it occurs shall be gradual, providing for some delay in the movement of radioactive materials in addition to that provided by the natural system.

- a) The package shall contribute to the overall safety as part of a system. Waste form, container, overpack and backfill functions shall be defined and interrelated.
- b) The waste package shall be designed to reduce potential exposures to the general public, bearing in mind the ALARA principle. (These criteria will be set by appropriate national and international authorities and will include consideration of the probabilities of occurrence of

various release and transport scenarios, as well as their consequences, i.e. individual and collective doses.).

- c) The package should provide containment for a period of time to contribute to the overall safety of the system. Any containment loss shall be gradual, resulting in only fractional release rates.
- d) Waste packages shall not contain chemicals that could interact adversely with barriers or other materials in the repository.
- e) The waste package and the total disposal system must be designed to prevent nuclear criticality.

3.4 Waste package characteristics

For the conditioner to address the above criteria, a set of characteristics shall be defined that can be related to both the criteria and the waste package. These characteristics are summarised as follows:

- 3.4.1 <u>Handling and identification</u> Physical size and standardized packages Package identification and records
- 3.4.2 <u>Operational period</u> Thermal loading and temperature (short term) Radiation stability Waste form/container compatibility Criticality safety Mechanical stability (fines, void space, surface area) Surface dose Contamination Gas generation, compressed gases Combustibility, pyrophoricity, explosives Chemical toxicants, corrosives, reactants Liquids, sludges, fines
- 3.4.3 <u>Post-sealing period</u> Thermal loading and temperature (long term) Radiation stability (radiation damage, volume change, waste form change) Chemical durability (leaching, solubility) Criticality safety Mechanical stability (void space, compressive strength) Reactivity with environment

Thus, the next three chapters of this report, rather than addressing each functional waste package criterion directly, addresses the functional criteria in terms of the above waste package characteristics. The pertinent characteristics will be identified for each aspect of the waste package life (i.e., handling and identification, operational period, and post-sealing period). They will be discussed in the context of how the characteristics can be controlled or maintained in order to satisfy the functional criteria.

4. HANDLING AND IDENTIFICATION

It is imperative that conditioned wastes are packaged so that, upon leaving the conditioning plant, they can be handled safely and identified throughout the operational phase, i.e., from the end of the conditioning operations and through transport, storage (whether it is at the site of the waste conditioner, at a special storage site, or is colocated with the waste repository) and emplacement in the repository.

4.1 Physical characteristics and the configuration of packages

The physical size will be determined by the waste conditioner and repository operator who shall consider jointly:

- a) the dimensions and weight of the container and the methods of handling at all stages, including emplacement in the repository;
- b) the waste loading and resultant heat release per container, for high-level wastes;
- c) the spacing in the repository;
- d) the cooling required during any storage prior to disposal.

From the points of view of the storage facility and repository operators, the use of standardized package sizes for repeatable handling should be desired through all the phases and over the life times of the operational phases of the facilities. Once the repository has been constructed, both the size of container and maximum heat release per container will have been agreed and fixed (see also Section 5.1).

It should be noted, however, that with no actual sites currently identified for a high-level waste repository, but with a number of Member States either operating or designing high-level waste immobilization plants (e.g., French AVM, Indian WIP, United Kingdom WVP), these plant operators have had to decide on package sizes which they believe will be acceptable to an eventual repository operator, in conjunction with the regulatory authorities, allowing for a period of storage for decay to take place and overpacks to accommodate physical requirements of the repository operator.

In the case of conditioned low- and intermediate-level wastes, the standardization of package sizes and types will be of greater importance due to the wide variety of types of wastes (with different levels of radioactivity) and the larger number of waste producers and conditioners who will be involved.

4.2 Package identification and records

It is essential that all packages should be identified individually when they leave the conditioning plant and through every phase of handling through to disposal so that their exact location is known. A standardized recording system should be developed so that the full history of the package is recorded. When a repository is finally sealed, all the package records for that repository should be assembled and placed in a suitable archive for safe keeping.

5. OPERATIONAL PERIOD

This chapter considers the way in which waste characteristics listed in Section 3.3.2 might be controlled in order to meet specified acceptability criteria during the operational period up to sealing of the repository. Sections 5.1 through 5.7 address characteristics pertinent to all wastes. Section 5.8 deals with characteristics specific to low- and intermediate-level wastes.

5.1 Thermal loading and temperature (short term)

One of the major factors in the design of a high-level waste repository is heat generation in the waste packages. The high-level waste contains nearly all of the heat-producing fission products that are present in radioactive waste and therefore generates significant levels of heat. Therefore, the high-level waste packages shall be designed and controlled to be thermally compatible with the repository. In terms of handling the waste packages, the level of decay heat output will be at a maximum at the time of conditioning. At this time, the conditioner shall handle safely and store temporarily the heat generating waste packages until such time that they are transported to either long-term storage or disposal facilities.

In order to determine the allowable heat generation rates from high-level waste containers, one must understand the heat decay characteristics of the waste. Figure 2 is an example of a decay curve for pressurized water reactor (PWR) fuel [15]. It can be seen that the decay heat drops by a factor of approximately ten in going from one year to ten years and by a similar factor from ten years to one hundred years out of the reactor. Therefore, the period of interim storage and time of waste emplacement in a repository are very critical to the resulting temperatures.

The repository operator (and regulatory authority) may set a maximum heat output for each high-level waste package. The age of the waste that corresponds to this maximum may also be specified since it is important that the decay characteristics be known for designing the repository. The repository temperature is determined by the combined heat output from all of the waste packages. The repository operator will be constrained by both repository and waste package temperature limits. The maximum repository temperature will only be reached after many years of repository operation, or possibly even after it has been shut down and sealed.

The contents of the individual waste packages partially determine the maximum temperature of the waste form and of the geological medium adjacent to the waste packages. There are several ways of reducing this maximum temperature, examples of which are reducing waste concentration, allowing radioactive



FIG. 2. Decay heat in high-level waste from PWR spent fuel [15]

decay and increasing the surface area of the container. These options can be controlled by the waste producer or conditioner. Whichever option or combination thereof is selected, the waste package must meet heat generation and size limitations established by the repository operator or regulatory authority.

Waste concentration reduction is achieved simply by putting less waste in a unit volume of container so that the container contains more matrix material and less actual waste.

Radioactive decay of the waste can be achieved during interim storage before and/or after conditioning the waste. One must, of course, respect regulations that may limit the period of storage of the waste before disposal.

The use of engineered barriers in the repository could increase the temperature of the entire waste package. The repository designer should have allowed for this when the maximum heat generation rate is specified for a waste package. However, the conditioner will have to give special consideration to whether the resulting repository temperatures have an adverse effect on his chosen waste form. If, for instance, the anticipated maximum centerline waste temperature at the time of disposal exceeds some specified maximum waste form temperature, then the conditioner will want to further reduce the heat loading at the time of conditioning. If waste packages are produced prior to disposal conditions being established, then storage or alternative means to provide heat decay shall be considered prior to disposal. Some thermal aspects of radioactive waste disposal in geological formations are presented in [16].

The conditioner can calculate the heat generation rate of the waste from an appropriate waste analysis. He can then determine the amount of waste that can be immobilized in a given container taking into account safety requirements and repository and transportation heat generation rate limits.

After the waste has been immobilized or conditioned, various methods for verifying the container heat generation rate can be used, for example, measurement of the container wall temperature under standard conditions of heat loss or calorimetric measurements.

The majority of temperature effects during the operational phase will be associated with high-level wastes. Conditioned intermediate-level wastes will not produce the same temperature effects in the repository but the waste form temperature may be high enough to have detrimental effects on the matrix such as swelling, polymer breakdown and gas formation. Examples of these wastes are activated materials, radiation sources and dissolver sludges.

5.2 Radiation stability

During the operational period, the main radiation effects are due to the decay of the fission products. While the bulk of the radiation dose to the solid will come from the actinides in the long term (see Section 6.2), these have little effect during the operational period even though alpha-decay causes at least 100 times more displacements per atom in the structural lattice of the waste form than beta or gamma decay. (See Table XXXIV in Reference [6].)

Radiation stability is relevant to all conditioned wastes and is likely to be of greater short term operational period significance for intermediate- and low-level wastes. Longer term radiation damage effects are discussed in Section 6.2.

5.3 Waste form/container compatibility

Initially most important is the protection of the immobilized waste form by an appropriate container during interim storage and the operational period of a disposal repository, so that total containment is assured. Thus, leaching of radionuclides is not consideration of high relevances during the operational period.

High-level wastes will be transported in type B shielded casks which are designed to withstand a series of stringent tests such that the contents cannot escape. The type B cask [14] does not require the contents to meet any criterion for the leaching of the waste form. Observance of safe transport regulations similarly makes leaching a relatively unimportant aspect during transport of low- and intermediate-level wastes even if conditioned wastes are to be transported under the proposed LSA III category.

The interaction of the immobilized waste form and/or coolant with the container material (in the short term) and with water typical of the disposal repository environment (in the long term) represent the major routes for the escape of radionuclides back into the human environment. The choice of the composition of an immobilized waste form can have an extremely important bearing on chemical durability, both in relation to the percentage of waste which is incorporated and also the choice of the additives to the waste to make the final waste form. Extensive literature has been published on the many immobilized waste forms proposed for high-level waste and on their durability [6,17,18] and also for low- and intermediate-level wastes [8].

For high-level wastes, however, it is important that the immobilized waste form should be compatible with the material chosen for the fabrication of the container into which it is placed for all subsequent transfers to disposal. A series of corrosion tests shall be formulated in agreement with the regulatory authority in which the waste conditioner can demonstrate no significant interaction between the waste form and the container for the probable duration from manufacture to emplacement in the repository. It is important to recognise that this period could be 50 years or more. During this period temperatures at the possible corrosion interface will be well above ambient. During some immobilization processes, the waste form may be in contact with the container at temperatures as high as 1000°C for hours or in some cases days. These interface temperatures will then decrease rapidly as the container is cooled, but could remain above 100°C for some years depending upon the sequence of events and conditions in storage (i.e., air cooled or water cooled). The corrosion testing programme must be realistic in relation to the possible temperature conditions both under normal circumstances and in any abnormal situation. The programme must also take into account possible interactions with the backfill and the host rock.

In the case of low- and intermediate-level wastes, conditions will be much more varied. These categories of wastes may be immobilized in cement, bitumen, polymers, etc. [8]. Due to the much larger volumes involved compared with high-level wastes, container materials are likely to be much cheaper and simpler (e.g., thin walled, mild steel; concrete; etc.). It is important that the container material be specified to provide adequate integrity for the operational period, particularly taking note of internal corrosion caused by the waste form and external corrosion from the outside environment. As intermediate-level wastes may have to be placed in interim storage for a lengthy period, as no repositories have been currently identified, there must be no deterioration of the container integrity during this period.

5.4 Criticality safety

Criticality can only occur if an unacceptably high level of fissionable material is immobilized with the waste. Maximum levels for these elements in the concentrated and immobilized waste should be established. In nearly all cases fissionable materials are not expected to be present in significant quantities to be a problem, so it is the non-routine or one-time occurrence that one should be guarding against.

Analysis of suspicious waste batches being introduced to the immobilization facility for fissionable materials will identify whether they are of concern. If fissionable materials are present in the waste, it might also be possible for these materials to concentrate in one portion of the waste or in the waste package. This might be especially true if there are opportunities for precipitation of certain elements during immobilization. In the case of potential segregation in the waste, one should fully understand the operation of the process and identify any opportunities for this to happen. Proper process controls, as well as monitoring the waste form, will eliminate the possibility of this occurring. The above is applicable to high-level waste and alpha-bearing, low- and intermediate-level wastes.

5.5 Mechanical stability

It is important that the waste package has a certain level of mechanical stability to maintain physical integrity after the waste form has been produced and during storage and repository operation.

The principal factors affecting integrity are thermal stress, internal and external pressure, and mechanical shock. Many currently proposed high-level waste forms are brittle and under stress could crack resulting in an increase in surface area which could lead to increased release of radionuclides by leaching or by dispersion of fines. Special attention to container integrity is required if the waste form is of a particulate nature. In the case of low- and intermediate-level wastes, the primary concern is to maintain container integrity during all aspects of handling. If the containers are standardized packages such as steel drums, there are established handling procedures which should be followed by the conditioner to minimize container damage during handling. Although fines should be of less concern than for high-level wastes, there should be an equivalent effort to prevent fines dispersion in the event of a handling accident.

Mechanical shock of the waste package may lead to an increased accessible surface area. Some data are available for containers of glass [6,17,] and are being generated for other waste forms [8]. The primary concern here is that impacts do not lead to respirable fines which would be of concern if the container broke open. A likely criterion is that the high-level waste container be designed to withstand credible dropping accidents without breaking open. This aspect also applies to low- and intermediate-level wastes immobilized with a matrix such as cement. The probability of a severe accident capable of cracking the waste form, producing fines and/or rupturing the container is low but in the case of such an accident remedial action will be necessary.

Waste form cracking and failure of the container due to mechanical shock can be minimized by the conditioner. He can fill the void space in the top of the container and establish maximum lift heights for the waste package. In addition, certain container designs are more resistant to impacts than others (e.g. rounded edges may result in less container breaking).

During the repository operating period it is likely that the compressive strength of the waste package will be of concern. In some cases the waste package will have to resist repository and stacking pressures. Additionally the package has to resist any internal pressure due to gas generation from the waste form. With respect to high-level waste forms, it is important that the conditioner understands thermal effects on his waste form so that he can use some degree of control to minimize potential cracking and loss of strength in the future. With this information he can programme the cooldown of the waste package and minimize potential cracking, specifically hot containers should not be quickly placed in cool environments such as water storage ponds. References [6] and [17] show the effect of thermal stresses on a high level waste glass after it has been cast in a container. Additional data have been accumulated for glass and need to be generated for other types of waste forms.

Any thermal or mechanical effects on mechanical stability could increase the surface area of the waste form. If a criterion is proposed for allowable surface area it will probably have to be complementary to the criteria for chemical durability. Thus, the conditioner may be able to make some trade-offs between leach rate and surface area. This point is dealt with in Section 6.3.

5.6 Surface dose

Surface dose rates from high-level waste containers (and also most intermediate-level containers as well) will be nigh and will require remote handling during all periods up to repository emplacement. The transportation, storage and repository systems will be designed to cope with these containers by providing adequate shielding during the remote handling. However, their designs will be based on a maximum container dose rate and therefore a criterion will be established. It is likely that the dose rate criterion will not be the critical one because the conditioner will already be limiting dose rate by limiting the maximum container heat generation rates.

5.7 <u>Contamination</u>

The control of surface contamination in storage, transportation and repository operations influences the radiation exposure to the work force. In addition, if the contamination is transferable, contamination within or outside the storage or repository environment can occur. Therefore, there will be criteria established to limit the amount of contamination, especially smearable, on the container surface. Even for remotely handled packages, it is desirable that the packages and handling systems remain as free of contamination as is reasonably practical.

The conditioner has several options available for controlling the waste package surface contamination. To begin with, his processing facility should be designed to isolate heavily contaminated areas from other areas needing greater cleanliness. He should also use good design features, such as leak-tight connectors and good ventilation systems. In spite of such designs, it is likely that the containers will have some contamination that will require physical removal. This removal can be accomplished using water, steam or chemical sprays or baths, or electro-polishing might be considered. If container decontamination is used, one must be careful to minimize thermal shock to the package. (See Section 5.5.)

For low-level waste containers where no shielding is required and direct contact handling is possible, it is even more important that surface contamination be controlled to acceptable levels which must be specified by additional criteria (particularly alpha contamination with plutonium contaminated material).

5.8 Other miscellaneous characteristics

As previously explained at the beginning of this Section, a number of the characteristics listed in Section 3.3.2 are of specific relevance to low- and intermediate-level wastes; each is briefly discussed in turn, together with comments regarding criteria.

5.8.1 Gas generation

With certain combinations of waste and matrix, e.g., when organics are present, there may be the possibility of the generation of gases. (This is particularly relevant in the long term due to radiation damage and is discussed in Section 6.2). If this is suspected, specific tests should be carried out to measure the release. Depending upon the porosity of the immobilized waste form, the rate of gas generation, the free space in the container and the overall volume of the container, the criteria should be drafted to ensure that the container cannot be pressurised to a level which could lead to distortion or premature failure during the operational period [11].

5.8.2 <u>Compressed gases</u>

If it is proposed to dispose of radioactive gaseous wastes by putting the gas in cylinders under pressure, these cylinders must be designed to withstand all possible disposal and accident conditions. (With respect to 85 Kr, a full account of the transport, storage and disposal is given in [19].)

5.8.3 <u>Combustibility</u>

Since many immobilized waste forms for low- and intermediate-level wastes involve the use of organic materials (e.g., bitumen, organic resins and polymers, etc.) the dangers and consequences of combustion must be assessed. Tests must be carried out to determine whether the waste forms could be ignited, and under what conditions; experience has shown that in most cases it is exceedingly difficult to ignite these materials under realistic fault conditions and that, even if they can be ignited, they do not burn, but only char.

5.8.4 Pyrophoricity

If wastes contain pyrophoric materials, particular attention should be paid to their conditioning and handling to ensure that there are no foreseeable risks during the operational phase. Wastes that are inherently pyrophoric should not be permitted in storage or disposal areas. They should be pretreated to eliminate this characteristic.

5.8.5 Explosives

Care should be taken in the choice of immobilized waste form to ensure that combinations of waste and matrix cannot interreact to provide a potentially explosive situation. For example, if chlorates are used for decontamination, these may react violently with certain organic materials. Wastes that are inherently explosive should be pretreated to eliminate this characteristic prior to storage or disposal.

5.8.6 <u>Chemical toxicants</u>

Special attention should be paid to wastes which contain toxic materials (e.g., cyanide, arsenic) to ensure that the risks of a release from the immobilized waste form are considered.

5.8.7 <u>Corrosive materials</u>

It is the responsibility of the waste conditioner to ensure that any corrosive materials in the waste are incorporated into the immobilized waste form such that the container and package integrity is not breached. However, the presence of such materials should be identified, since should there be a release, they should not jeopardise other waste packages.

5.8.8 Freeze/thaw cycle

If wastes are immobilized in cement and the packaged waste form is stored temporarily outdoors, attention should be paid to possible damage which could result from temperature cycling due to changes in weather conditions, specifically if temperatures cycle above and below freezing.

5.8.9 Free liquids

No free liquids should be left in waste packages. Absorbents should be incorporated in excess to avoid any risks of free liquids being present.

6. POST-SEALING PERIOD

This chapter covers those characteristics which should be considered when the repository has been shut down, backfilled and all penetrations have been sealed, i.e. the repository has been filled with packaged waste to its capacity and/or no further waste is to be disposed of at the site. From this time, the waste is not subject to direct control and criteria should be considered for the post-sealing period.

The lifetime of a high-level and alpha-bearing waste repository can be divided into three phases:

- a) The phase immediately following emplacement of the waste in the repository when there is appreciable heat release and both the far field as well as the near field of the repository and its surroundings will have reached a maximum temperature and begun the very gradual reduction in overall temperatures as the radionuclides decay. This period may extend over several hundred years. Should water gain access to the wastes during this period, leaching will be accelerated due to the elevated temperatures (hydrothermal effects).
- b) The second or middle phase begins when the bulk of the fission products have decayed and covers the time over which the bulk of the actinides decay, i.e., it extends over a few thousand years until temperatures have essentially reached the ambient temperature of the host rock. During this period it is unlikely that any hydrothermal effects will take place, but leaching may take place at temperatures somewhat higher than ambient.
- c) The third phase is when there is no significant decay heat and extends until the radionuclides have all decayed to insignificant levels. Leaching may take place at ambient temperature.

For low- and medium-level waste only phase two and three apply and for short-lived, low-level waste only phase three applies.

6.1 <u>Thermal loading and temperature (long term)</u>

The high-level waste package should have reached a maximum temperature soon after emplacement in the repository; however, the host rock may not reach its maximum temperature for several years and, in some cases, not until after the repository has been shut down and sealed. One might suspect that repositories would normally be large and would have operating periods up to approximately fifty years. Maximum temperatures would thus be reached during the operational period which was covered in Section 5.

The long-term effects of temperature have a potential impact on the waste package and on the rock surrounding the

The temperatures of the package were much more repositorv. significant during the operating period (Section 5.1) due to the relative high heat generation rate. However, during the operating period there is less concern about temperature induced effects that become important when the long term is considered. For instance, it is possible to have a long-term degradation of the waste form if it is held at prolonged high temperatures. If this is important, the conditioner might want a further reduction in the waste package heat loading below the limit identified in the original repository operating license. The effect of elevated temperatures also plays an important role in chemical durability, since the corrosion of the waste package and the leaching of the waste form are strongly temperature dependent (see Section 6.3). However, waste packages may be designed to last up to several hundred years, then the temperature beyond that time will probably be sufficiently low that concerns about "hydrothermal" effects will be minimal.

These thermal factors shall be considered by the repository designer and should be taken into consideration when he establishes maximum container heat loadings at the time of emplacement. He can assume that significant quantities of water are not present in the proximity of the waste containers during the operating period. The open repository coupled with high temperatures and ventilation and pumping, if necessary, would remove moisture from the repository. However, after the repository is closed, water may accumulate near the waste containers. Therefore, the waste package designs have to account for possible increased corrosion of barrier materials due to elevated temperatures. The temperature effects beyond the period of total waste package containment are discussed under chemical durability (Section 6.3).

Other long-term effects are potential stress to the rock formations and uplift of the repository overburden due to thermal swelling. These are not the conditioner's responsibility and are considered by the repository operator when he establishes waste container heat generation rate limits and average repository loadings (kW/hectare).

In summary, the major factors affecting temperature are heat generation rate of the waste package, the barriers which are placed around the package which act as insulators and increase the package temperature, and the spacing of the containers. Spacing establishes the average heat loading of the repository (kW/hectare) and the maximum repository temperature. Of these three factors, the conditioner only has direct control over the waste package heat generation rate. To determine the maximum quantity of waste that can be placed in the waste container, one should take into account the operating period and waste form factors discussed in Section 5.1 as well as the barrier and long term repository temperature factors discussed above.

Thermal loading and temperature are of less importance for both low- and intermediate-level wastes although for some

alpha-bearing wastes there will be a long period when temperatures are above ambient.

There is a strong body of opinion which is suggesting that the container and overpack should be designed to remain essentially intact during the first heat dissipation phase. It is somewhat more debatable whether it would be necessary to design and guarantee that it also remains intact during the middle heat dissapation phase. In fact, it should be assumed that the first failures will occur near the beginning of the middle phase.

Once the conditions of the groundwater for leaching of the waste form have been agreed upon (section 6.3.1), a series of corrosion tests should be carried out on candidate container and overpack materials, taking particular care to consider possible enhancements of corrosion attack which may occur at welds, etc. These tests must cover the temperature regime from the maximum design temperature of the repository down to the ambient temperature and must enable both a generalised corrosion rate to be determined to assess the time to failure for the containers, and also to enable a prediction of the statistical failure rate of the containers. These data, and other data on backfill and host rock barriers can be utilized to predict a waste package lifetime.

6.2 Radiation stability

Stability of the immobilized waste form due to the effects of radiation damage from the decay of the nuclides is an important property to be considered. A detailed discussion of the effects of radiation can be found in References [6, 17, 18]. The main long-term effect is due to the alpha decay which causes at least 100 times more displacements per atom in the lattice structure than beta or gamma decay. Ninety percent of these displacements are due to the recoil nucleus from the alpha decay. Effects of alpha decay which are to be taken into account can include:

- volume changes
- stored energy, which could be spontaneously released later, giving some temperature rise
- helium generation
- increases in leach rate
- cracking of the immobilized waste form, thus creating a greater surface area

Since the effects of damage due to radiation, particularly alpha, are only long term, it would not be possible to obtain meaningful information from a study of actual samples of the final immobilized waste form containing the radionuclides. However, it is possible to simulate the long-term effects due

to alpha-decay by incorporating short-half-life alpha-emitters into the proposed immobilized waste forms. In a few years of testing, it is possible to accumulate the dose effects which will occur over $10^4 - 10^6$ years. Measurements of all the effects listed above have been made for a wide range of glasses and in most cases have been shown to be sufficiently small that they will not affect the waste form over the long term. However, more work is required with some of the newer waste forms currently being proposed for high-level wastes and for certain low- and intermediate-level wastes which contain high levels of alpha activity (e.g. organic waste forms). All the studies of the effect of alpha emitters have been accompanied by the measurement of the leach rates of both irradiated and unirradiated samples, and no changes have been measured of more than a factor of two, and in most cases the changes have been less than 50% and probably within experimental error.

However, it is most important that the effects of alpha decay should not be simulated too rapidly, as this can then lead to more serious damage which is unrealistic of the real situation [20].

If a waste conditioner proposes to produce a new, untested waste form, he should carry out tests similar to those described above to demonstrate that his proposed immobilized waste form will not seriously deteriorate during the long term. Such a series of tests should be agreed between the conditioner, repository operator and also the regulatory authority.

The radiation stability of low- and intermediate-level immobilized waste forms has been described in [8]. In order to interpret these published results it is necessary to take into account the less well defined nature of the immobilized waste form, together with wide variety of waste types and matrix materials.

In general, integrated doses will be in the range $10^8 - 10^9$ rads (beta, gamma) and most results have indicated that the immobilized waste forms can withstand such doses. However, the effects of the integrated doses of alpha-radiation are not well established.

When organic ion-exchange resins are immobilized, there is the possibility that high absorbed doses of radiation might lead to resin swelling due to changes in the resin structure. If cement is used as the matrix material, this swelling could result in cracking and a general weakening of mechanical properties.

It is necessary to examine the effects of radiolytic gas generation (due to alpha decay and decomposition of organic materials) and swelling of the waste matrix due to the integrated radiation dose. Radiolytic gas generation is unlikely to be a problem with the cement matrix due to its porosity. It has been concluded that the limitation on the maximum permissible activity in cement, bitumen and polymer matrices will be determined by the gas release and swelling rather than by an increase in leach rate. Experience generally suggests that 1 Ci/l of beta, gamma loading is acceptable for bitumen and nearer to 10 Ci/l of beta, gamma loading for cement.

Excessive gas generation from any waste form can lead to undesirable pressurization of the containers.

As discussed for high-level wastes above, the waste conditioner should carry out tests to demonstrate the resistance to radiation damage of any new, untested immobilized waste form proposed for each waste type.

6.3 Chemical durability

The most important phenomenon to be considered in the long term is the eventual release of radionuclides from the waste form and repository into the environment due to contact between water and the waste form. We must, therefore, consider a number of areas where criteria may be relevant, especially for high-level wastes:

- a) the lifetime of the container and overpack materials under all conditions relevant in the repository. It will be necessary to consider both corrosion rates of the materials used for the containers and overpacks and also the probability of premature failure (e.g., due to localised corrosion because of welds or enhanced corrosion due to a change of physical chemical conditions). Container lifetime was discussed in Section 6.1. Information from Section 6.3 will aid in lifetime determination.
- b) leaching under hydrothermal conditions (i.e., failure of or no use of long-life waste packages)
- c) the effect of the hydrothermal conditions on the backfill and near-field host rocks, and the possible migration and sorption of the radionuclides through these near-field materials. It is particularly important to determine if these hydrothermal conditions will adversely affect the backfill materials and their sorption capacity when the radionuclides are eventually leached out of the waste form.
- d) leaching under conditions that are above ambient, but not hydrothermal.
- e) leaching under essentially ambient conditions, but relevant to the probable environmental conditions actually pertaining in the repository.
- f) the migration and sorption of radionuclides released from the waste form into the surroundings, both near field and far field back to the human environment.

Each of these areas will be considered in turn for high-level wastes; comments regarding low- and intermediate-level wastes will be made separately.

6.3.1 Leaching of high-level wastes

6.3.1.1 Leaching under hydrothermal conditions

The overall analysis of the repository should consider the possibility of premature failure of a few containers and overpacks during the hydrothermal period. The significance of this evaluation is dependent on the severity of the hydrothermal conditions which are determined by factors discussed in Section 5 (e.g. waste loading in the containers and time of interim storage). It will be necessary to carry out tests in which representative samples of the waste form are leached at elevated temperatures. There will almost certainly be design limits for individual repositories of 100 - 200°C, above which the engineered barriers are not designed to operate.

It is important not to confuse such tests with the Soxhlet leach test which is generally operated at or near 100°C using recirculating distilled water. While a useful and quick test for the laboratory study of trends in waste form properties, it bears very little resemblance to the true environmental conditions.

The test should use water representative of the locality in which the repository will be sited. Particularly, attention should be paid to the dissolved solids already present in the groundwater, the pH, Eh and also [HCO3]⁻ concentration. Modification of the local groundwater by the backfill materials, other engineered barriers (e.g., concrete) and the corrosion products from the container and overpack should also be taken into account. Finally, it is necessary that the rate of contact of the water with the waste form should be representative of the repository situation. It is probable that the groundwater flow will be very slow and that an equilibrium solubility will be reached between the water and waste form at the elevated temperature. These saturated conditions will significantly lower the leachability of the waste form. Reference [21] provides information pertinent to leaching of the waste packages.

6.3.1.2 Effect of hydrothermal conditions on the near field

The near-field host rocks will be disturbed by the repository excavation and the heat generation rate of the waste packages. It will be necessary to study the chemical, physical and mechanical properties of the host rock at both elevated temperatures and under possible hydrothermal conditions. It will be necessary to determine changes which could occur in these properties and, in particular, to measure the effect on both the possible rates of migration of groundwater and the sorption of released radionuclides. Similar experiments will also be required for the possible backfill materials.

One aspect of these tests will be to evaluate them under realistic overall conditions, i.e., to ensure that the radionuclides used to measure the rates and sorption are exactly the same as the form in which they are released from the waste form. In practice, it may be essential to combine the two experiments. Both the leaching and sorption tests should be conducted over time periods which will enable predictions to be made for the overall modelling of the system during the hydrothermal period.

These-near field tests should be the responsibility of the repository operator rather than the waste conditioner. These data on the near-field properties will provide information which will aid in determining the necessary waste package properties.

6.3.1.3 <u>Leaching under conditions that are above ambient</u> (non-hydrothermal)

The tests outlined under 6.3.1 must be carried out under the conditions which prevail beyond the hydrothermal period while the temperature is still above ambient. If the packages fail, it will most likely occur during this time period. The tests shall be made under conditions as close as possible to those anticipated in the repository. Some of the fission products will have decayed to insignificant levels during this period.

6.3.1.4 Long-term leaching under ambient conditions

The tests outlined under 6.3.1 should be conducted under the ambient conditions of the repository and only with the long-lived fission products and actinides that are still present. Radionuclides that were leached during earlier time periods may be re-immobilized by sorption, and precipitation processes.

6.3.2 <u>Chemical durability of low- and intermediate-level</u> wastes

Many low- and intermediate-level wastes will be stored and disposed of at near ambient conditions. Other intermediate-level wastes will contain sufficient heat generating isotopes that localized repository temperatures could be above ambient and the effects on the durability of the waste forms need to be evaluated. The waste form leach tests should be carried out at ambient or above ambient temperature conditions in a similar manner to those tests for high-level waste. That is, the leach tests should simulate the repository conditions as closely as possible. Because of the very long period that the waste will be exposed to these ambient conditions, one can probably assume that the packages have failed, and thus, no credit should be allowed for the containers.

The period of concern for short-lived low- and intermediate-level wastes is such that one need not give great importance to either high or very long-term durability. On the other hand, the long-lived, low- and intermediate-level alpha containing wastes may require sufficient conditioning to provide necessary chemical durability. There are also some low- and intermediate-level wastes that are of such low toxicity that they will not warrant a great deal of conditioning. Care should be taken that the combination of waste and matrix does not have potential chemical reactivity which in the long run could alter the properties of waste forms.

6.4 Migration and sorption of released radionuclides

For radionuclides that have been leached into solution, their migration and sorption behaviour on and through the host rock and back to the human environment have to be investigated under conditions similar to those described above. The release from the waste form may occur in two ways; some of the radionuclides will be leached out and almost immediately sorbed on the backfill or host rock so that rates of migration are very slow; other radionuclides may be leached in a form in which they are not readily sorbed and they migrate at essentially the rate of movement of the groundwater in the host rock. It is important to identify in which extent radionuclides (of those of radiological importance) fall into which category. While it is unlikely that the waste form can be modified to reduce the rate at which these poorly sorbed radionuclides leach out, it may be possible to consider alternative backfill materials which are more effective.

These tests should be the responsibility of the repository operator.

6.5 Criticality safety

It is essential to consider the fissile content in each waste package to avoid any risks of criticality. There is a further long-term aspect to consider. During the lifetime of the waste packages in the disposal repository, the packages may deteriorate and fissile elements may be leached out. These may be sorbed on either backfill materials or within the host rock. It is essential to consider possible reactions in which such fissile nuclides may be preferentially concentrated in the immediate surroundings. Criteria should be developed to provide limits on the levels of fissile nuclides in the wastes or in the way in which the waste packages might be emplaced in the repository to eliminate the risk of criticality from such processes. The moderator effect of any water which will eventually be present in the location must be taken into account. The above may be applicable to high-, intermediate- and low-level wastes which contain high concentrations of alpha emitters.

6.6 Mechanical Stability

Long term mechanical stability is primarily concerned with compressive strength of the waste package. The surface area of the waste form is also important but this factor was covered under Section 5.5 because it is during the pre-repository emplacement period that increases in the waste form surface area due to thermal and mechanical shock would occur. The effect of long-term compression of the waste package is difficult to assess. If the compression is isotropic, glass will be much stronger. If the compression is not uniform, some crushing can occur. There may be crystalline waste forms that are not compressed to their maximum density at time of emplacement but it is likely that further isotropic compression in the repository would not lead to increased surface area. This aspect requires experimental confirmation.

The factor which is important is crushing of the waste package so that the container is breached, prematurely permitting water into the container. The conditioner can reduce the probability of this happening by filling the void space in the top of the waste container, and therefore, a criteria should be considered for void space filling. There are other means of controlling crushing due to compression within the repository; however, these are probably more within the jurisdiction of the repository operator. For example, the backfill material may possibly be utilized to absorb part of the compression; however this would require further The repository operator may also be concerned with evaluation. major accident situations where potential shearing of the waste packages could occur. If required, the operator will have to design the repository to accommodate this highly unlikely occurrence, rather than the conditioner.

There are no identified long-term mechanical stability considerations that need be considered for either low- or intermediate-level wastes, other than those generally discussed above for high-level wastes. Depending on the toxicity of these wastes, one can have less stringent requirements.

6.7 Reactivity with the environment

In addition to the thermal effects and long-term leaching, a number of other factors should be considered.

In certain circumstances, thick walled overpacks have been proposed for high-level wastes which can act as in-built shielding and which are integral with the waste form and container through to the final disposal. It is important to consider the effect of these overpack materials; for example, if lead is used, this could gradually dissolve and saturate the near field around the repository, thus destroying the sorptive capacity for the radionuclides. In addition, if the package materials are toxic, their migration into the human environment should be considered along with that of the radionuclides.

In the case of many low- and intermediate-level wastes, the immobilized waste form may be organic, and any migration of this into the surrounding host rock may be deleterious. Similarly, many complexing agents are used for decontamination purposes. If these retain their chemical form even after immobilization, then the implications of their eventual release in a repository must be considered since they could have a marked effect on nuclide mobility in the host rock.

Consideration should also be given to possible microbiological attack on organic waste forms which could lead to degradation of the waste form and enhanced leaching or even formation of gaseous products. For example, the presence of Thiobacillus in groundwater in the vicinity of a repository could bring about oxidation of sulphides to sulphates.

6.8 Modelling of overall system

The overall system modelling is the responsibility of the repository operator and regulatory authority.

The main pathway-to-man analysis of the overall system can be modelled once the data identified in the previous sections 6.3.1 - 6.3.5 have been obtained. These models will then enable criteria to be developed for both the repository construction materials and the waste form and container/overpack. It will be important to balance the cost versus the benefits in order to determine the extent of waste conditioning required and the need for any other engineered barriers to be coupled with the natural barriers of the specific repository site.

(For further information on modelling see, for example, paper No.IAEA-SM-261/44 presented at the Utrecht Symposium, June 1982.)

7. CONCLUSIONS

- 1. The choice of conditioning process for any particular waste type should be based on consideration of the conditioning technology available, the required stability of the waste form, safety assessments of the entire waste management system and economic considerations. The long-term performance of the conditioned waste under disposal conditions is not necessarily the overriding factor; in the case of many types of low- and intermediate-level waste, transport and storage requirements may be more stringent than those related to the long term, from both the economic and the radiological protection points of view.
- 2. Waste acceptance criteria are the responsibility of the regulatory authorities, after consultation with the repository operator and waste conditioner. Even site specific criteria which are developed by the storage and disposal system designers/operators will have to be approved by the regulatory authorities. These authorities should hot specify arbitrary criteria or criteria which cannot be applied in practice (e.g. because it is not possible to demonstrate compliance with them). They should also ensure that criteria are based on the results of safety assessments and do not impose more stringent requirements and hence more financial expenditure than are warranted.
- 3. There are numerous characteristics for which criteria can be written in a straight-forward manner although in some cases site-specific data are required. These are:
 - physical size and configuration of package
 - package identification and recording system
 - criticality safety
 - surface dose
 - surface contamination
 - combustibility, pyrophoricity and explosives
 - gas generation and compressed gases
 - free liquid
 - chemical toxicants, corrosives and reactants
- 4. Radiation and mechanical damage of the waste forms may affect leaching by factors which can be directly determined; therefore, where data are available, criteria for radiation and mechanical stability can be derived.

- Chemical durability is by far the most difficult criterion 5. to establish, particularly in the case of high-level waste where temperature effects are important. To formulate a chemical durability criterion for the post-disposal phase, it is necessary to establish firstly a performance objective for the whole waste package; this should be in the form of a release rate, as a function of time and predicted repository conditions. Criteria on waste container durability and waste form durability can then be derived from this performance objective. Throughout this process the disposal system should be viewed as a whole, since releases from the waste package can be compensated by means other than those related to chemical durability (e.g. by use of appropriate back-filling materials, by storage for decay, by waste concentration control prior to disposal and by limiting repository operating temperatures).
- 6. The releases by leaching and the subsequent radionuclide migration and retardation sorption effects in the host media and surrounding geological formations need to be evaluated. Other reactions with the environs need to be considered in this evaluation. Data from [5] and [6] above can be used in mathematical models to assess system radiological safety and can provide valuable input for the development of waste acceptance criteria. At present calculations are being carried out for generic disposal systems and R&D currently being performed will provide the data for the detailed safety assessments.
- 7. It is essential that the total system from waste conditioning through to disposal should be analyzed in the development of waste acceptance criteria.

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