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QUALITATIVE ACCEPTANCE CRITERIA FOR RADIOACTIVE WASTES TO BE DISPOSED OF IN DEEP GEOLOGICAL FORMATIONS

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FOREWORD

This report is part of the IAEA's programme on underground disposal of radioactive wastes in which the Agency has been active for many years.

Initially, the work of the Agency was focused on general criteria for underground disposal of radioactive active waste and the Agency report "Criteria for Underground Disposal of Solid Radioactive Wastes", IAEA Safety Series No. 60, was published in 1983.

Later the disposal of intermediate level wastes and of those containing short lived radionuclides in shallow ground was given priority since there was a need in many Member States for guidance in this area and the Agency's report "Acceptance Criteria for Disposal of Radioactive Wastes in Shallow Ground and Rock Cavities", IAEA Safety Series No. 71, was published in 1985.

The present report is linked to the Agency's Safety Standards document on "Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes" (IAEA Safety Series No. 99, 1989). It is concerned with the disposal of high level, intermediate level and alpha bearing wastes and sets out qualitative waste acceptance criteria for use in developing deep geological repository concepts.

The first draft of the present text was prepared in Vienna by a group of consultants in June 1985. Further drafts were prepared by an Advisory Group Meeting in Vienna in January 1986, the Technical Review Committee on Underground Disposal of Radioactive Wastes (TRCUD) in February 1986, a Consultants' Meeting in Vienna in March 1987, the TRCUD in February 1988 and by S. Wingefors (Sweden) and the Agency's Scientific Secretary I.F. Vovk. Final revision was carried out by D.W. Clelland (United Kingdom) in October 1989.

Those who contributed to the preparation of this document, and to whom the Agency wishes to express its gratitude, are given in the list of participants below.

EDITORIAL NOTE

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1. INTRODUCTION

1.1 Background

The objective of a radioactive waste disposal system is to ensure that man will not suffer unacceptable detriment from the disposed wastes at present or in the future.

With the aim of providing IAEA Member States with basic guidance on protection of humans from the hazards associated with deep geological disposal, an internationally agreed set of principles and criteria has been published in an Agency's Safety Standards document on "Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes" (IAEA Safety Series No. 99, 1989) [1]. Its intention is to form a basis for specifying more detailed standards and criteria for use in the subsequent stages of development of underground waste disposal concepts.

Generally, the efficiency of a disposal system depends upon a number of components - the waste form, the waste package, the backfill material, the geological formation and the surrounding environment. These components should be selected and/or designed to be compatible and to achieve the required degree of isolation.

In the longer term, the isolation capability of a waste disposal system will depend on the combined performance of its components. Therefore, it is necessary that an overall system approach is applied in the repository development. This implies that any less favourable characteristics or deficiencies in one component can be compensated for by adding or, improving the performance in, another component thereby so achieving the required degree of isolation for the whole system.

Since the nature of the waste and its packaging is an important component of a waste disposal system, their minimum level of performance should be defined by responsible national authorities. A basis for such definition includes the waste acceptance criteria which specify the characteristics of the waste form and its packaging which have to be fulfilled before acceptance for disposal. To ensure compliance with criteria, a quality assurance programme for waste conditioning and packaging is required.

The present Safety Guide has to be seen as a companion document to the IAEA Safety Series No. 99 [1]. It is concerned with the waste form which is an important component of the overall disposal system. Because of the broad range of waste types and conditioned forms and variations in the sites, designs and constructional approaches being considered for deep geological repositories, this report necessarily approaches the waste acceptance criteria in a general way, recognizing that the assignment of quantitative limits to these criteria has to be the responsibility of national authorities.

1.2 Objectives

The main objective of this Safety Guide is to set out qualitiative waste acceptance criteria as a basis for specifying quantitative limits for the waste forms and packages which are intended to be disposed of in deep geolgoical repositories. It should serve as guidance for assigning such parameter values which would fully comply with the safety assessment and performance of a waste disposal system as a whole.

This document is intended to serve both national authorities and regulatory bodies involved in the development of deep underground disposal systems.

1.3 Scope

The qualitative waste acceptance criteria dealt with in the present Safety Guide are primarily concerned with the disposal of high level, intermediate level and long-lived alpha bearing wastes in deep geological repositories. Although some criteria are also applicable in other waste disposal concepts, it has to be borne in mind that the set of criteria presented her shall ensure the isolation capability of a waste disposal system for periods of time much longer than for other waste streams with shorter lifetimes.

With respect to the intention of some Member States to use the deep geological disposal concept also for other types of wastes, especially short lived, it is expected that the criteria presented here will cope with all requirements arising from these waste streams.

The high level waste in this Safety Guide comprises the highly radioactive materials originating from the reprocessing of irradiated nuclear fuel and any other waste with similar radioactivity levels, but also spent reactor fuel, if it is declared a waste.

The criteria do not address any retrieval of the waste after the closure of the reporisitory.

1.4 Structure

The Safety Guide begins with an overview of definitions to assure proper understanding and interpretation of the key terms used in the document. A detailed description of waste types and forms is followed by a characterisation of the most existing deep geological disposal options being considered worldwide. A subsequent section is dedicated to a procedure, presented in general terms, for the identification and development of waste acceptance criteria. In the next section, a number of generic and qualitative criteria are given together with guidelines for their quantification.

The Safety Guide is supplemented with a bibliogrpahy and with a list of drafting and reviewing bodies who have participated in the preparation of this document.

2. DEFINITIONS

The following defintions are intended to assure proper understanding and interpretation of the key terms used in this Safety Guide. They have been taken from IAEA-TECDOC-447, the Radioactive Waste Management Glossary [2]. Some terms which are not contained in that document have been defined in a sense in which they are commonly used in the radioactive waste management field, others should be considered as an explanation in the context of this document only.

backfill: The material used to refill the excavated portions of a repository or of a borehole after waste has been emplaced.

barrier (natural or engineered): A feature which delays or prevents radionuclide migration from the waste and/or repository into its surroundings. An engineered barrier is a feature made by or altered by man; it may be part of the waste package and/or part of the repository.

biosphere: That portion of the Earth's environment inhabited by any living organisms. It comprises parts of the atmosphere, the hydrosphere (ocean, seas, inland waters and subterranean waters) and the lithosphere.

chemical durability: The ability to withstand the effects of chemically induced processes such as corrosion, dissolution, phase transformations, etc.

closure: Final sealing of the repository.

competent authority: A national authority designated for a specific purpose by a Government of a Member State.

conditioning of waste: Those operations that transform waste into a form suitable for transport and/or storage and/or disposal. The operations may include converting the waste to another form, enclosing the waste in containers, and providing additional packaging.

confinement of waste: The segregation of radionuclides from the human environment and the restriction of their release into that environment in unacceptable quantities or concentrations.

containment: The retention of radioactive material in such a way that it is effectively prevented from becoming dispersed into the environment or only released at an acceptable rate.

criteria: Principles or standards on which a decision or judgement can be based. They may be qualitative or quantitative. Acceptance criteria are set by a regulatory authority. (Some Member States use terms such as 'protection goals' instead of 'acceptance criteria'.)

deep geological formation: Rock formations such as rock salt, argillaceous formations or crystalline rocks at depths suitable for the construction of deep underground repositories.

deep underground repository: Underground cavities developed in geological formations at depths intended to provide long term isolation of high level and long-lived radioactive wastes. Normally only depths larger than 200 m in dry formations and 500 m in water-bearing formations are considered. (N.B. Disposal in rock cavities and sub-seabed disposal are not considered as deep underground disposal.)

disposal system: see waste disposal system

emplacement: The placement of a waste package in its final repository location.

heat producing waste: Radioactive waste which by radioactive decay generates heat within the waste and its surroundings in such quantities that it must be considered during handling, transportation, storage and when disposed in a repository.

high level waste:

(i) The highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous waste from the first solvent extraction cycle and those waste streams combined with it).

(ii) Spent reactor fuel, if it is declared a waste.

(iii) Any other waste with a radioactivity level comparable to (i) or (ii).

implementing organization: The organization (and its contractors) that performs activities in order to select and investigate the suitability of a site for a nuclear facility, and that undertakes to design, construct, commission, operate and shut down such a facility.

intermediate level waste: Waste of a lower activity level and heat output than high level waste, but which still requires shielding during handling and transportation. The term is used generally to refer to all wastes not defined as either high level or low level.

isolation of waste: See confinement of waste.

lithosphere: A broad general term which refers to the upper rigid part of the Earth's crust.

long lived radionuclides: For waste management purposes, a radioactive isotope with a half-life greater than about 30 years.

long lived waste: Waste that will not decay to an acceptable activity level in a period of time during which administrative controls can be expected to last.

long term: In waste management, refers to periods of time which exceed the time during which administrative controls can be expected to last.

low level waste: Waste which, because of its low radionuclide content, does not require shielding during normal handling and transportation.

multi-barrier: A system using two or more independent barriers to isolate the waste from the human environment. These can include the waste form, the container (canister), other engineered barriers and the emplacement medium and its environment.

operational period: The period of time when waste packages are prepared for disposal and emplaced.

overpack (used as a noun): A component added to previously conditioned waste to provide additional functional capability.

overpack (used as a verb): Application of a component as described above.

packing: A component which may be used with waste packages for disposal which is generally located between the waste container and the host rock.

packaging: See waste packaging.

post-sealing period: The period after a waste repository has been shut down and sealed.

quality assurance: Planned and systematic actions necessary to provide adequate confidence that an item, facility or person will perform satisfactorily in service.

quality control: Actions which provide a means to control and measure the characteristics of an item, process, facility or person in accordance with quality assurance requirements.

radioactive waste: Any material that contains or is contaminated with radionuclides at concentrations or radioactivity levels greater than the 'exempt quantities' established by the competent authorities and for which no use is foreseen.

regulatory authority: An authority or system of authorities designated by the Government of a Member State as having the legal authority for conducting the licensing process, for issuing of licenses and thereby for regulating the siting, design, construction, commissioning, operation, shutdown, decommissioning and subsequent control of nuclear facilities (e.g. waste repositories) or specific aspects thereof. This authority could be a body (existing or to be established) in the field of nuclear-related health and safety or mining safety or environmental protection, vested with such legal or environmental protection, vested with such legal authority, or it could be the Government or a department of the Government, or it could be an international agency.

repository: An underground facility in which waste may be emplaced for disposal.

repository operator: The organization responsible for the operation of the repository.

repository system: A repository and all its supporting facilities.

shallow ground disposal: Disposal of radioactive waste, with or without engineered barriers, above or below the ground surface, where the final protective covering is of the order of a few metres thick.

short lived radionuclide: For waste management purposes, a radionuclide with a half-life shorter than about 30 years.

short lived waste: Waste which will decay to a level which is considered to be insignificant from a radiological viewpoint, in a time period during which administrative controls can be expected to last.

shutdown and sealing: Action taken, after disposal operations have ceased, to prepare an installation for abandonment or minimum surveillance.

site: The area containing a nuclear installation (e.g. a waste repository that is defined by a boundary and which is under effective control of the implementing organization.

storage: The placement of waste in a facility with the intent that it will be retrieved at a later time.

underground disposal: Disposal of waste at an appropriate depth below the ground surface.

waste conditioner: The responsible organization for the facility where the waste is conditioned. The waste can be subsequently conditioned at many places, e.g. for transportation and storage at the site of generation and for disposal at the disposal facility.

waste disposal system: a combination of geological environment, a repository and waste packages emplaced in the repository.

waste form: The physical and chemical form of the waste (e.g. liquid, in concrete, in glass, etc.) without its packaging.

waste management: All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste.

waste owner: The organization which holds title to the waste.

waste package: The waste form and any container(s) as prepared for handling, transportation, storage and/or disposal. A cask or overpack may be a permanent part of the waste package or it may be re-usable for any waste management step. The waste package may vary for the different steps in waste management.

waste packaging: Any component or assembly of components which is applied to a waste form during conditioning to prepare it for disposal.

waste producer: The responsible organization for the facility where the waste is generated or conditioned.

3. BASIC INFORMATION ON THE WASTES AND MANAGEMENT SYSTEMS

3.1 General

The IAEA has recently proposed six categories of solid radioactive waste with respect to disposal [3]. They are based on the half-lives of the radionuclides and on the activity level of the waste which may require the use of shieldings and, in some cases, take into account the heat output. These categories are set out in Table 1.

TABLE 1. GENERAL CHARACTERISTICS OF WASTE CATEGORIES WITH REGARD TO DISPOSAL

classification linked to handling

classification linked to disposal	shielding/heat	shielding	no shielding	--
long-lived heat	Category I High-level waste			
long-lived		Category II Long-lived intermediate-level waste	Category III Long-lived low-level waste	
short-lived		Category IV Short-lived intermediate-level waste	Category V Short-lived low-level waste	
--				Category VI Exempt waste

The preferred disposal options have been identified in previous IAEA Safety Series reports [4-6] and the criteria for disposal of solid radioactive waste have been set out in other IAEA documents [7, 8]. This Safety Guide will deal with waste categories I, II and III and with spent fuel, if it is to be disposed of in a repository. Spent fuel may require disposal in countries operating an 'open' fuel cycle which does not involve reprocessing and plutonium recycle.

3.2 Radiation protection objectives

In the development of waste acceptance criteria, the prime objective is to provide the required radiological protection of man in accordance with internationally agreed radiation protection principles during waste conditioning and packaging and the operational and post-operational phases of the repository.

The system of dose limitation recommended by ICRP [9] and incorporated in the IAEA Basic Safety Standards [10] is generally accepted by national authorities. This is based on the three fundamental principles,

- justification of a practice,
- optimization of radiation protection, and
- limitation of exposure to individuals.

During waste conditioning and packaging and the operational phase of disposal, the application of these principles is well established and accepted, as it is basically the same as at other facilities for the handling and processing of radioactive materials.

The ICRP has given recommendations [11] on the application of radiation protection principles for the long term aspects of radioactive waste disposal. Work in this field is also being carried out by the OECD/NEA [12] and by several national authorities, which have decided to adopt deep geological disposal [13-16]. National authorities may use this background information to develop guidelines for the post-operational radiological protection requirements of deep geological repositories.

3.3 Regulatory considerations

The responsibilities of national regulatory bodies depend upon national policies, legislation and regulations and consequently a standard scheme for a regulatory framework cannot be given. The national regulatory authorities in individual countries will develop and implement regulatory procedures, the main aim of which are to ensure that the waste is handled safely from the time of its generation to its final disposal and that it is effectively confined within the geosphere afterwards. An IAEA report on regulation of underground repositories for disposal of radioactive wastes has been published [17].

3.4 Waste characteristics

3.4.1 General

The characteristics of the waste may have a major effect upon the performance of the disposal system. In the following subsections an outline is given of the sources and types of waste, the forms of conditioned waste and waste packaging.

3.4.2 Sources and types of waste

3.4.2.1. High level waste (Category I) and spent nuclear fuel

High level waste and spent nuclear fuel (if declared a waste) are both characterized by the emission of decay heat due to the presence of large amounts of fission products in high concentration. This release of thermal energy is of importance in the design of a repository where the heat will pass from the waste form through its packaging and other barrier materials around the waste package and will be dissipated in the surrounding host rock formation. The rate and duration of the heat release will affect the physical and chemical processes involved in barrier and host rock performance.

Other waste types, especially fuel cladding materials, might also give rise to significant heat generation, although to a lesser degree and of shorter duration.

High level waste originates from the reprocessing of spent nuclear fuel. Its radionuclide content depends upon the type, enrichment, and burnup of the fuel and the time elapsed after the discharge of the fuel from the reactor. The waste, which is collected and stored at reprocessing plants in the liquid form, must be solidified before disposal. Generally, in order to reduce the effect of fission product decay heat and radiation during conditioning and later in the disposal stage, the liquid waste and conditioned product are stored for periods of time to allow sufficient decay of fission products.

Disposal of spent nuclear fuel without reprocessing is an option being considered in some countries. Before emplacement in a repository, the spent fuel will usually be stored at the reactor or in an interim storage facility, thus providing for some decay of heat-producing radioactivity which will facilitate the subsequent conditioning, transport and disposal.

3.4.2.2 Other wastes for disposal in deep geological formations (Categories II and III)

These wastes originate mainly from reprocessing of spent nuclear fuel and from plutonium fuel fabrication operations. The main wastes in these categories are, fuel cladding materials, spent ion exchange resins, plutonium contaminated materials and other redundant equipment.

Since most of these waste types contain appreciable quantities of alpha emitting radionuclides, it is generally considered that they too must be permanently isolated from man's environment, preferably by deep geological disposal. The main difference between the wastes in Category II and those in Categories III is the absence of necessity for shielding in the latter.

3.4.3 Waste forms

3.4.3.1 General

The term waste form refers to the physical and chemical form of the waste within its packaging.

Operations which transform waste into a form more suitable for transport, storage or disposal are termed conditioning of the waste.

Special methods of conditioning are employed to solidify or immobilize liquid wastes since free liquid must be avoided in waste packages. In addition, conditioned waste should be monolithic in nature and not an easily dispersed particulate material.

The term waste package means the waste form and any container for handling, transportation, storage or disposal. A cask or overpack may be a permanent part of the waste package or it may be reusable. The waste package may vary at different stages in the waste management procedure.

3.4.3.2 Heat generating wastes (Category I)

High level waste. Several processes for the solidification of high level waste have been developed and tested. However, only vitrification (i.e. the incorporation of radionuclides into a glass matrix) has as yet reached the stage of full-scale industrial application. Other processess under development include incorporation into ceramic, crystalline or mineral-like matrices.

In the vitrification process the glass matrix is based on borosilicates, and the solid form has a number of desirable properties, such as thermal stability, radiation resistance and low leach rate. This process has been extensively reported in the literature [18-21].

Spent nuclear fuel. The main objective of conditioning spent nuclear fuel is to provide a corrosion resistant containment. In some countries the reference concept involves direct encapsulation of spent fuel assemblies in a suitable container. However, in order to achieve sufficient radiation shielding and at the same time preclude nuclear criticality it might prove necessary to surround the fuel by a dense matrix or stabilizer [22]. With the object of volume reduction other concepts involve consolidation of fuel pins, which have been removed from assemblies, in a suitable container [23].

Other heat generating wastes. Heat generation in waste types other than high level waste and spent fuel, e.g. fuel cladding materials, is generally produced by decay of activation products with relatively short half-lives. Typically, these wastes are stored for a period before conditioning to allow the activation products to decay to acceptable levels followed by incorporation in a suitable matrix, e.g. cement.

3.4.3.3 Non-heat generating wastes containing significant quantities of alpha bearing nuclides (Categories II and III)

Although the wastes in this category have low content of beta/gamma emitters they are not suitable for shallow ground disposal because of their alpha activity levels and long radioactive half-lives and should be routed to deep geological disposal.

In principle, all radioactive waste relating to the nuclear fuel cycle might contain alpha emitting radionuclides. It is, therefore, of great importance that appropriate limits on concentrations of alpha bearing nuclides are set for short lived wastes (categories IV and V) if a separation between deep geological disposal and, for example, shallow ground disposal is desired. Depending on the depth of disposal, these limits may range from 10 to 10^4 Bq/g [24] and, for practical reasons, they have to apply as an average for each waste package.

The treatment and conditioning of low and intermediate level wastes is dealt with in several publications [18, 25 and 26].

Liquid and wet wastes. Numerous methods for conditioning of alpha bearing wastes have been tested, but only very few have been applied in full-scale operations. The most important are solidification in cement or bitumen, or packaging of the dried material.

At present cementation is believed to be appropriate for most purposes. A relatively high degree of radiation shielding can easily be provided and the process is flexible.

Bituminization can give a product with good leaching properties although the long term behaviour of this waste form is uncertain at high waste loadings [27]. Bitumen is a combustible material and this must be taken into account in conditioning, subsequent handling, transportation, and disposal.

Both cementation and bituminization are capable of providing good retention of alpha emitters.

Solid wastes. Combustible waste may be incinerated to reduce the waste volume [28], however, special care should be taken when alpha emitters are present in high concentrations. The ashes may be incorporated into a cement or bitumen matrix or may be compacted by high pressure to reduce the possibility of dispersion.

Non-combustible wastes may be compacted, reducing the waste volume by factors up to 10 and/or they may be encapsulated in a matrix such as cement. The latter might be appropriate for the more highly active wastes. It should be noted that decomposition of organic materials in a repository might give rise to complexation and gas generation [28].

3.4.4 Waste containers

The use of containers for wastes and spent nuclear fuel is a necessary pre-requisite for handling, transportation, storage and emplacement operations.

After emplacement the use of containers ensures complete in situ containment of wastes for the physical life of the container. For certain periods of time, after the container failure, the backfill materials surrounding the primary package, may undertake the containment function by hindering or, at least, slowing down the release rate of radionuclides.

The development of waste packages to achieve desired performance targets should be carried out on a repository and site specific basis. Factors which should be considered are, the geochemical environment, the groundwater characteristics, the hydrostatic and lithostatic loads, and the thermo-mechanical properties of the host rock. The effect of radiation and heat upon the host rock and groundwater should also be considered.

3.5 Transportation

Requirements for the safe transport of radioactive materials are regulated by most national authorities according to the basic IAEA transport regulations [29]. These regulations detail criteria on the waste package for transportation including such factors as radionuclide inventory, heat load, and mechanical strength.

3.6 Deep geological repositories

3.6.1 General

Waste acceptance criteria for deep underground disposal are influenced by the repository design and the gelogical medium chosen. It should be noted, however, that the design of a repository is also directly dependent on the site specific conditions and on the characteristics of the waste for disposal.

Disposal systems are designed to provide, not one, but a series of barriers between the waste and man (the multi-barrier concept), each intended to prevent, delay, or minimize the release of radionuclides. The following are examples of barriers in such systems,

- favourable properties of the waste form such as chemical durability, low leachability and low dispersibility,

- waste containers,

- backfill (sometimes termed buffer) materials surrounding the primary waste package,

- the host rock formation, and

- the environment which lies between the repository and man.

The effectiveness of the multi-barrier system may be such that a large degree of redundancy is involved in the isolation of the radioactive wastes. This should be regarded as a favourable property of the system design.

3.6.2 Suitable geological formations

Several types of geological formations are currently being considered as sites for radioactive waste repositories [30, 31],

- evaporitic rocks (e.g. rock salt),
- argillaceous formations (e.g. clays and shales), and
- hard rocks (e.g. granites, gabbro, gneisses and tuff).

The properties and characteristics of candidate formations have been discussed in detail in the literature [31].

3.6.3 Repository concepts

The choice of site and the layout of a repository are dependent on several factors,

- the nature and type of the waste arisings,
- the geology of the site,
- regulatory requirements,
- the available technology, and
- costs.

It shold be borne in mind that the choice may also be influenced by other factors of political or socioeconomic nature, such as local public attitudes, ownership of sites, etc. In some countries, these factors may dominate the final decision.

At present, the concepts for deep geological repositories (at depths from 200 m to more than 1000 m) may be grouped as follows:

- mined cavities,
- mined cavities with emplacement boreholes, and
- deep boreholes.

3.6.4 Backfill

Backfill materials surrounding the primary waste package are included in most repository concepts [32] with the following objective,

- to restrict the ingress and egress of groundwater,
- to condition the groundwater to a more favourable chemical state,
- to retard the release of radionuclides by sorption,

- to act as a plastic buffer protecting the waste materials from mechanical damage caused by stresses and displacements of the host rock,
- to interact chemically with the waste container materials and develop a protective layer, and
- to promote heat transfer from the waste containers to the host rock.

Backfill materials commonly considered are, concrete, clay, sand, vermiculite, magnesia, crushed rock, or mixtures of these to provide the desired functions. Backfill materials should be compatible with the waste container material and with the host rock, taking into account thermal and radiation effects in the vicinity of the package. In some concepts the backfill in an emplacement cavity is considered as a part of the waste package.

4. DEVELOPMENT OF WASTE ACCEPTANCE CRITERIA

4.1 General

In general, criteria for an underground disposal system can be related to the geological environment, the repository or the waste [7]. This document deals specifically with the acceptance criteria for only one component of the system, the waste, and is focussed on qualitative waste acceptance criteria for disposal in deep geological formations.

As the disposal system as a whole must be considered in safety assessments, it is not possible to establish generally valid quantitative waste acceptance criteria because the geological environment and the engineering concept at each repository will be different. Consequently, the safety of each individual disposal system must be demonstrated in site specific analyses of the operational and post-operational phases. These analyses will form a basis for establishing quantitative waste acceptance criteria.

In this section a procedure is presented, in general terms, for the identification and development of waste acceptance criteria. In the next section a number of generic and qualitative criteria are given together with guidelines for their quantification.

4.2 Major steps in criteria development

The development of a disposal system and of the waste acceptance criteria for it is an iterative process from a first generic approach to the finally licensed site and approved procedures. Three stages can be identified in the development of waste acceptance criteria,

- at the initial planning stage criteria are defined in a very general form on the basis of the overall waste disposal strategy and general information on the types and quantities of wastes that have arisen or are expected to be generated. The availability of certain host rocks are recognized at this stage and disposal options identified. The preliminary qualitative and very general criteria developed are useful for a first safety assessment.

- after the area survey and preliminary site selection has been started the general characteristics of potential disposal sites are known and a more detailed safety assessment of the disposal system can be made. At this stage an iteration between waste package characteristics and repository design may lead to the formulation of preliminary quantitative criteria.

- at the site confirmation stage the final characteristics of the disposal system are established and a final safety assessment leads to the definition of quantitative waste acceptance criteria.

After licensing and the start of disposal operations, the waste acceptance criteria may be modified to reflect operating experience, technical development and scientific progress.

4.3 Bases for criteria

It should be recognized that mechanisms which can result in the release of radionuclides will be different in both operational and post-operational phases. During the operational stage, the waste packages shall withstand all foreseeable abnormal handling conditions. In the post-operational stage, the major processes which can adversely affect the isolation capability of a disposal system will be the gradual degradation of conditioned wastes and their containers and the disruptive events potentially occuring in the future and affecting the repository and its environment.

Thus, to meet the overall safety objectives, the following requirements shall be fulfilled:

- the waste form, container, overpack and backfill shall be compatible with repository and its environment.

- the waste package shall satisfy the regulations for the transport of radioactive materials.

- the surface dose rate and surface contamination of the waste packages shall be commensurate with safe handling procedures.

- in case of abnormal handling the waste packages shall be capable of withstanding credible impacts without unacceptable dispersal of radioactive material.

- the waste package shall not contain materials that might lead to inadvertent release of activity or interact adversely with barriers or other materials in the repository, i.e. free liquids, explosive, pyrophoric or highly inflammable materials, or corrosive agents, and

- fissile materials in the waste must be limited to prevent criticality, and

- the package should provide complete containment for a substantial period of time. Any subsequent loss of containment should be gradual.

5. WASTE ACCEPTANCE CRITERIA

The criteria presented in this document provide general guidance in technical areas related to waste acceptance, for which more specific criteria should be developed by the appropriate national authorities.

In this chapter a number of qualitative waste acceptance criteria are given. They are of a sufficiently generic nature to cover most existing options for disposal in deep geological formations. The accompanying text provides guidance information that might be useful in quantification of the criteria.

5.1 Waste form and waste package criteria

5.1.1 Radionuclide inventory

CRITERION: The type, characteristics and contents of radionuclides in the waste package should be known with sufficient accuracy to ensure compliance with authorized limits and should be documented accordingly.

Limitations on the acceptability of wastes for disposal in a deep geologic repository may include specific activities and total quantities of radionuclides in the wastes. These should be approved by the competent national authority.

For spent fuel and high level wastes, the radionuclide inventory is primarily dependent upon fuel type, enrichment, burnup, and the time elapsed since the fuel was discharged from the reactor. For high level wastes, the radionuclide inventory may be determined by direct measurement during conditioning. For spent fuel, the radionuclide inventory may be estimated using suitably validated computer codes [33].

For intermediate and low level alpha bearing wastes the radionuclide inventory must be controlled by suitable quality assurance procedures to ensure that authorized limits will not be exceeded.

5.1.2 Thermal power, thermal loads, and thermal effects

CRITERION 1: The thermal power output of the waste packages shall comply with limits applicable for storage, transportation and handling prior to emplacement.

CRITERION 2: The thermal power output of the waste forms shall be limited such that any associated changes to physical, chemical and mechanical properties of the waste form, waste package components, other engineered barriers and repository components and the host rock do not adversely affect the safety of the overall disposal system.

Prior to disposal, the thermal power output of wastes must be limited so as to allow handling, storage and transportation operations in accordance with national regulations. Limitations on thermal power output shall also be established for all repository operations.

In establishing the limiting thermal output of a waste package, the effects on all waste package components and other engineered barriers, as well as the time dependent temperature fields which result from the presence of all other heat sources in the repository, must be considered [32]. A detailed discussion of the effects of heat on the performance of deep geological repository components has been published in the literature [34, 35]. The determination of limits for thermal power should be made based on data from measurements and tests conducted under actual site specific conditions or close simulations thereof.

For high level wastes, the total thermal output may be reduced by prolonged storage prior to disposal. The specific heat output may be reduced by reducing the proportion of waste to matrix. Maximum glass temperatures in the vitrified glass product of 400-500^{o}C have been identified to avoid such phenomena as phase separation and devitrification of borosilicate glass [36]. High level waste thermal outputs may be estimated directly from the radionuclide inventory using suitably validated computer codes [33].

The thermal output of spent fuel waste packages may be controlled by prolonged storage prior to disposal, or by varying the quantity of spent fuel per package. A temperature limit of from 350^{o}C to 400^{o}C has been identified to limit the possible failure of cladding due to stress rupture [37].

For heat generating intermediate level alpha bearing wastes, thermal output can be determined and controlled through the radionuclide inventory using appropriate calculational techniques. Limits on thermal output are mainly dependent upon the immobilization matrix used.

5.1.3 Nuclear criticality

CRITERION: Waste packages shall be designed to preclude nuclear criticality of a single waste package. Handling, storage and disposal systems shall be designed and operated to ensure that criticality of arrays of waste packages cannot occur.

For spent fuel, there will be a significant quantity of fissile material present in waste packages such that single-package criticality may be possible. In this case, suitable engineered safeguards (i.e. insertion of a suitable nuclear poison in the waste package, or use of a "filler" material to eliminate voids) may be necessary.

For high level wastes in vitrified form, criticality is normally not a concern because of the typically low fissile material inventory. For other alpha bearing wastes, the content of fissile material in waste forms will also generally be low compared to spent fuel, such that single-package criticality may be controlled by specification of a suitably low total fissile inventory. However, where significant quantities of fissile material are present in the waste, conditioning methods should be evaluated to ensure that segregation and local concentrations of fissile materials will not occur.

In the long term it is also necessary to consider the possibility of leaching of fissile material from the waste and the possibility of local reconcentration of these materials.

5.1.4 Radiation effects, radiation damage and contamination control

CRITERION 1: External radiation dose rates of conditioned waste packages shall be in compliance with the limits for facilities and equipment in which they will be handled, stored and transported prior to emplacement in a repository.

CRITERION 2: Transferable radioactive contamination on the exterior of waste packages should be maintained within limits established for storage, transportation, and packaging facilities where wastes are to be handled.

CRITERION 3: Radiation dose rates shall be controlled to levels sufficient to ensure that radiation-induced processes (such as radiolysis) and degradation of material properties of the waste package, repository components and the host rock do not occur to an unacceptable degree.

Competent national authorities should establish limits on package radiation levels to ensure the protection of workers and the public during normal operations. Control may be established by limiting radionuclide inventories during conditioning, or by use of supplemental shielding in the package. For most waste disposal systems this is not expected to be a limiting criterion.

Detailed discussion of the effects of radiation on waste forms and their packagings has been published in several documents [20 32, 38, 39].

In establishing the limitations on beta-gamma radiation to the backfill and the host rock, radiation induced effects such as radiolysis of the groundwater, radiolytic decomposition of air in an unsaturated medium, and of the backfill and host rock constituents must be evaluated. Limits should be set to maintain these effects at acceptable levels with respect to their long term impact on waste package components and engineered barriers. The limits should be based on experimental data obtained under site specific conditions and performance analyses based on validated models.

The effects of radionuclide decay, especially recoil from alpha decay on the waste form material must be evaluated, and limits established to maintain waste form material properties at acceptable levels. Limits on total alpha decay dose may be based on accelerated radiation tests of simulated waste forms, containing short lived alpha emitters to give total exposures approximating those expected for actual waste.

For high level wastes, external radiation doses may be controlled by adjusting the proportion of waste to matrix material during conditioning, by using a thick walled container to provide shielding, or by storage for decay of the waste prior to conditioning. Borosilicate glasses have been shown to be rather insensitive to alpha recoil damage because of their amorphous character and generally low concentrations of alpha emitters [40]. Crystalline waste forms may be more susceptible to alpha recoil damage.

For spent fuel, effective control of external radiation doses can be obtained by prolonged storage prior to encapsulation or by providing a thick walled container for shielding. Because of extensive damage to the fuel caused by fission in the reactor, additional damage due to alpha recoils in spent fuel is insignificant.

For some intermediate level alpha bearing wastes external radiation levels may be high. These may be reduced by solidification in a dense matrix or by providing an external shield.

Control of surface contamination during the operational phase is necessary to minimize occupational radiation exposure, to limit the potential for spread of contamination to uncontrolled areas, and to facilitate maintenance of handling equipment which is exposed to the same environment as the waste container.

Contamination limits should be established for all waste types which have undergone conditioning through packaging, based on compliance with regulations set by the responsible national authority.

5.1.5 Mechanical stability, mechanical strength, and stress resistance

CRITERION 1: The waste packages must be able to withstand stresses arising without unacceptable deterioration in their ability to accomplish safety related functions.

CRITERION 2: Waste packages shall be designed such that, in conjunction with handling systems, releases due to mechanical impact under foreseeable incidents are limited to acceptable values.

Stresses which must be withstood might arise from normal handling and transportation loads during the operational period, from internal pressure due to gas generation or release, from external pressure due to lithostatic and hydrostatic loads, and from temperature gradients.

Preservation of assigned functions may require special design features in the waste package and/or the engineered barriers. For example, the performance of a tailored backfill or packing material might depend on the material's ability to retain its configuration. Thus, if a tailored packing material is to be used, voids within the waste package might have to be precluded in order to prevent collapse of the packing material.

For intermediate and low level alpha bearing wastes, the primary concern is maintaining the integrity of the containment boundary, and possibly of the waste form, throughout the operational period. However, the possibility of swelling of waste forms that contain certain materials, e.g. dehydrated salts and ion exchange resins, might have to be considered even for the long term [27].

Waste containers must be capable of sustaining a drop of a specified height, and other similar likely occurrences, without breach. The volatility and dispersibility of the waste form as well as the physical stability of the packaging should be evaluated to determine if adequate containment is provided. Foreseeable incidents and their consequences must be identified based on specific design features of storage, handling and disposal [41] facilities.

5.1.6 Combustibility and thermal resistance

CRITERION 1: High level waste packages, and spent fuel waste packages shall not contain combustible materials which could burn under normal repository conditions or foreseeable incidents. Intermediate and low level alpha waste packages containing combustible materials may be acceptable if the containers are non-combustible or heat resistant and do not support combustion under foreseeable incidents.

CRITERION 2: Waste packages shall be designed, so that, in conjunction with handling systems, releases due to thermal impact under foreseeable incidents are limited to acceptable values.

Combustibility is the ability of the waste package and waste form to be ignited and burn under normal repository conditions and foreseeable incidents. High level waste and spent fuel are typically treated and packaged in non-combustible forms.

Intermediate and low level alpha waste may contain appreciable amounts of organic materials (paper, bitumen, resins, and polymers) and require evaluation of its fire potential. This evaluation should include tests to determine the conditions under which wastes could be ignited. Experience indicates that it is difficult to ignite most of these materials under the conditions of foreseeable incidents.

The potential for fire can be reduced significantly by segregating wastes into flammable and non-flammable types and providing appropriate packaging.

Thermal impacts could occur in the operational phase, e.g. caused by a fire during transportation within a mined repository. In the detailed planning stage of a repository it is possible to evaluate existing combustible material that could affect the waste packages if it should be ignited. It has to be decided by the responsible authorities whether a fire can be precluded because of operational or administrative measures or has to be assumed for assessment purposes. In the latter case it is necessary to determine the temperature development of the fire and its duration as well as the behaviour of the waste packages under these conditions [41].

For some repository layouts it might also be necessary to consider thermal resistance of waste packages with regard to the temperature increase in the near-field after emplacement.

5.1.7 Gas generation

CRITERION: Gas generation in the waste package or in surrounding media should not jeopardize the performance of the overall disposal system.

Gases may be generated by radiolysis, radionuclide disintegration, chemical reactions between the waste and its matrix, corrosion of waste package materials, or decomposition of organic materials. Spent fuel elements may contain gases injected at the time of manufacture (e.g. light water reactor fuel pins) and gases generated by the fission process. Breach of spent fuel cladding can release these gases to the interior of the waste package.

For intermediate and low level alpha wastes, gas generation may be caused by decomposition of organic materials induced by radiation and thermal effects or microbiological attack. Gas generation may also occur in the host rock due to radiolysis of the groundwater or of the host rock.

Gas generation may result in container pressurization, failure of engineered barriers, creation of more corrosive environments, or the dispersion and direct release of radionuclides.

Container pressurization is not expected to be a significant problem with high level wastes and spent fuel. For intermediate and low level alpha wastes, conditioning should ensure that unacceptable releases due to pressurization do not occur during the operational period.

Gas generation around high level waste and spent fuel packages should be considered. It may be necessary to provide shielding to reduce doses or to provide more resistant backfill materials.

5.1.8 Free liquids

CRITERION: The quantity of free liquids in waste packages should be sufficiently low to ensure that the performance of the overall disposal system is not jeopardized.

For high level wastes, conditioning methods are expected to eliminate free liquids. For spent fuel, although damaged fuel pins may contain small amounts of water, this is not expected to present a significant problem in practice.

For intermediate and low level alpha wastes, conditioning methods should ensure that presence of free liquids does not result in the spread of contamination in the event of container breach and in the container degradation from within.

5.1.9 Explosive and pyrophoric materials, fire and explosion hazards

CRITERION: Waste packages containing materials that might cause explosion or ignition hazards shall not be accepted for disposal.

Wastes which contain explosive or pyrophoric materials, or materials which may interact to produce an explosion, should be conditioned to remove this hazard prior to acceptance for disposal.

5.1.10 Compressed gases

CRITERION: Containers of compressed gases should not be accepted for disposal.

Because of the stored energy of compressed gases (radioactive and/or non-radioactive), it is difficult to ensure their containment during disposal. However, if circumstances compel it, disposal of compressed gases should be undertaken only under special regulatory authorization.

5.1.11 Toxic and corrosive materials

CRITERION 1: The contents of non-radioactive toxic and hazardous materials should be known with sufficient accuracy to ensure compliance with authorized limits.

CRITERION 2: Waste forms should not contain materials which will corrode the waste containers or other barriers in the disposal system.

Low and intermediate level alpha bearing wastes may contain non-radioactive materials which are toxic and hazardous (e.g. mercury, cyanide and arsenic). These wastes should be evaluated for their total potential hazard and any requirements for treatment, conditioning or disposal should be established by competent national authorities.

Waste package materials should be compatible with the waste form. For low and intermediate level alpha wastes, conditioning should neutralize or immobilize materials which may be aggressive to waste packages.

5.1.12 Chemical durability

CRITERION 1: The chemical durability of the waste package should be sufficient to provide the required containment of radionuclides in the disposal environment.

For high level wastes and spent fuel, waste packages may be required to provide complete containment of wastes for periods of several hundred years or more. For low and intermediate level alpha wastes, containment may be required only for the operational period with no post-operational containment period.

To meet containment requirements, container materials compatible with the repository and the host rock environment must be selected. In the selection of materials possible failure modes should be considered, including general corrosion, local corrosion, stress corrosion cracking and reactions which could alter material properties and cause early failures such as hydrogen embrittlement.

For all waste types, significant retention of radionuclides by the waste form may be necessary to meet overall safety standards [42]. However, although the radiation properties have often been considered as an important characteristic of the waste form, it has also been shown that the barrier function of waste containers can be of importance if the transfer time of radionuclides to the biosphere is long (more than 1000 years) [43].

The mechanisms by which radionuclides are expected to be released and transported from waste repositories are associated with the presence of groundwater. Percolation of groundwater through breached containers, leaching of radionuclides from the decomposed waste form and their dissolution are processes governing groundwater contamination. Additional processes, such as formation of colloids and complexes, will depend on actual groundwater chemistry. In unsaturated zone repositories, direct release of gaseous radionuclides to the atmosphere must also be considered. For spent fuel, breach of fuel pin cladding could release entrapped gases which may include radioactive components.

Secondary containers and backfill should be used to enhance the radionuclide retention performance of the waste package. For example backfill may be used to, retard the flow of groundwater to and from the container, adjust the chemistry of the groundwater, reduce the solubility of radionuclides, reduce the potential for colloid formation or retard gaseous releases by sorption.

Waste package performance under disposal conditions may be confirmed by results of tests which simulate repository conditions and theoretical modelling to extrapolate laboratory test results to long time periods.

A more detailed discussion of chemical durability of wastes and related factors may be found in published documents [44, 45].

5.1.13 Physical dimensions and weights

CRITERION: The physical dimensions and weights of waste packages should be compatible with provisions for transport, handling and emplacement.

Compatibility with pre-existing capabilities is obviously desirable to the extent practical. However, special circumstances may warrant enhancement of existing capabilities. Where waste form and repository development work are proceeding in parallel, the waste producer and repository operator should agree to these parameters, especially waste package design.

5.1.14 Unique identification

CRITERION: Each waste package for emplacement in a repository should be marked with a unique identification.

The identification should be recorded with the content and all relevant characteristics of the waste package. The identification markings should be durable for the required period of time.

Package identification is necessary to ensure safe handling, appropriate emplacement, accountability, radioactivity control, criticality control, inventory control and certification of compliance with specifications.

An inventory control system should be established to record the receipt of all wastes and document the manner and location of waste emplacement in the repository. Recording quantities of wastes and locations within the repository will help to assure proper thermal loading (for heat-producing wastes), and in location and retrieval of waste packages if this is required. Upon shutdown and closure of the repository these records will document the contents of the repository.

5.2 Quality assurance criteria

Quality assurance of the waste packages as a part of the overall quality assurance programme for all activities from siting to closure and for all components of the disposal system should be established. Appropriate technical measures and organizational structures have to be adopted for this purpose.

5.2.1 Responsibilities and organization

CRITERION: Before acceptance of the waste for disposal, a programme of quality assurance should be established and responsibilities assigned, including responsibility for the quality of the waste and waste packages.

The development of a quality assurance programme has been described in published documents [46-51]. The responsibilities and authorities of key personnel and organizations should be defined together with the organizational structure within which activities are to be performed.

The organizations responsible for quality control of the waste should demonstrate and record that the quantitative waste acceptance criteria are being followed.

The quality of waste packages received for disposal should be checked by the repository operator to ensure compliance with the waste acceptance criteria. This control should be partially performed at the repository, at the storage facility of the waste producer and by an independent product control institute. Waste packages which do not comply with the requirements should be returned for reconditioning.

Tests and inspections of the conditioning process of the waste packages should be carried out routinely. Suitable tests and inspections should be developed and applied. Inspections of conditioning processes may be undertaken by the waste producer, waste conditioner or repository operator, depending on specific contractual arrangements. The operator of a repository is responsible for ensuring that only properly certified waste packages are accepted for disposal.

Supervision of waste production, waste conditioning and repository operation should be carried out by the national authorities including periodic audits of the quality assurance programme.

5.2.2 Quality control

Quality control of waste packages ensures compliance with waste acceptance criteria and aids the repository operator.

It is necessary to identify the properties of waste packages which have to be controlled. These can be checked by,

- control of the conditioning process, and
- checks on waste packages.

The most appropriate method of quality control, which is necessary but uses minimum effort, should be selected.

5.2.2.1 Control of the conditioning process

CRITERION: Control of the conditioning process should assure the required quality of the waste form and other parts of the waste packages.

The quality assurance of radioactive waste packages should preferably be carried out within the conditioning process (system-orientated control). It should be shown by inactive and active test runs that, under specified operating conditions, the conditioning process is able to produce waste packages of the required quality. Specifications including ranges and bandwidth of all essential process parameters of the conditioning process should be developed.

The process should be instrumented to measure and record the relevant process parameters to show that the process has been operating within the specified limits. Frequent inspections of the conditioning process complete the control.

5.2.2.2 Checks on waste packages

CRITERION: Checks on waste packages should be made to assure the quality of the waste form and other parts of the waste package.

The relevant properties of waste packages can be checked with non-destructive or destructive test methods (product control). Due to inherent difficulties e.g. the need for conditioning of secondary wastes and reconditioning of waste packages, product control should preferably be carried out by non-destructive methods.

5.2.2.3 Records

CRITERION: The results of the quality control should be recorded.

All the relevant data of the waste producer, conditioner and the repository operator should be recorded. The record systems of the parties involved should be compatible to allow information exchange. It should be the responsibility of the competent national authority to decide the duration of record retention.

5.2.3 Compliance with codes and standards

CRITERION: Waste forms and waste packages shall be certified as being in compliance with applicable codes and standards prior to acceptance for disposal.

Applicable codes and standards will be as determined by the competent national authorities.

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