IAEA-TECDOC-563

SITING, DESIGN AND CONSTRUCTION OF A DEEP GEOLOGICAL REPOSITORY FOR THE DISPOSAL OF HIGH LEVEL AND ALPHA BEARING WASTES

A TECHNICAL DOCUMENT ISSUED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1990

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IAEA, VIENNA, 1990
IAEA-TECDOC-563
ISSN 1011-4289

Printed by the IAEA in Austria
June 1990

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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.

The information contained in this document covering Siting, Design and Construction of a Deep Geological Repository for the Disposal of High Level and Alpha Bearing Wastes, has been prepared at the summary level for decision makers and technical managers. Its aim is to provide basic guidance for repository siting, design and construction based on the approaches and experiences of IAEA Member States.

The document outlines a basic technical approach to siting a geological repository. It describes the protection objectives, system performance assessment and the components of a repository system and their interrelationship, as well as the constraints on repository construction.

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 and alpha bearing wastes, and the technical objectives can generally be achieved through an iterative process that integrates the detailed technical information collected through the various phases of investigations, detailed design, performance assessment and construction.

The first draft of the present text was prepared in Vienna by a group of consultants in September 1988. Further drafts were prepared by an Advisory Group Meeting in Vienna in April 1989, a Consultants' Meeting in September 1989, and the Agency's Scientific Secretary made final revisions to the present document.

The Agency wishes to express its gratitude to those who participated in the preparation of this document, and the List of Contributors is noted at the end of the report.

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1. INTRODUCTION

1.1 Background

For about the last hundred years radioactive substances have been known to exist in nature. Their generation and decay has been observed. Humans have learned to make use of them and to handle them safely. When the generation of electricity from nuclear fission became a practical reality, basic techniques for dealing with the unavoidable radioactive wastes were required, and investigations for the management of these wastes were initiated. The amounts of the high level and alpha bearing components of these wastes are small in volume, have concentrated radioactivity, and are of high toxicity and hence require isolation from the biosphere. Currently, all radioactive waste containing long lived components in biologically significant concentrations is kept in intermediate storage. Monitoring, surveillance and maintenance provide a very high degree of certainty in the efficacy of isolation of such intermediate storage.

Several options have been investigated or considered for long term management of these wastes. Extreme options including shooting or rocketing into the sun or outer space, or transmutation into short lived or inactive nuclides by neutron irradiation do not provide a satisfactorily safe or economic solution. An international consensus has emerged that disposal in repositories constructed within suitable deep geological formations can ensure the adequate confinement of the radioactive wastes from the biosphere by using multiple barriers designed to meet national protection objectives. Moreover, examples can be found in nature where stable geological formations have isolated radionuclides for many millions of years.

1.2 Objectives

The main objective of this document is to summarize the basic principles and approaches to siting, design and construction of a deep geological repository for disposal of high level and alpha bearing radioactive wastes, as commonly agreed upon by Member States. This report is addressed to decision makers and technical managers as well as to specialists planning for siting, design and construction of geological repositories for disposal of high level and alpha bearing wastes.

1.3 Scope

The siting, design and construction of a deep geological repository for the disposal of high level and alpha bearing wastes is a major long term project involving many technical disciplines and it may also require broad social acceptance. The prime safety requirement is to satisfy the protection objectives. These technical objectives can generally be achieved by an iterative process that integrates the detailed technical information collected through the various phases of investigation, detailed design, performance assessment and construction. By this process, which is described in the report, the design is brought into balance with the characteristics of the chosen site and the social expectations of each country.

This document is intended to provide Member States of the IAEA with a summary outline for the responsible implementing organizations to use for siting, designing and constructing confinement systems for high level and alpha bearing radioactive waste in accordance with the protection objectives set by national regulating authorities or derived from safety fundamentals and standards of the IAEA. The protection objectives will be achieved by the isolation of the radionuclides from the environment by a repository system, which consists of a series of man made and natural safety barriers. Engineered barriers are used to enhance natural geological containment in a variety of ways. They must complement the natural barriers to provide adequate safety and necessary redundancy to the barrier system to ensure that safety standards are met.

Because of the long timescales involved and the important role of the natural barrier formed by the host rock, the site selection process is a key activity in the repository design and development programme. The choice of the site, the investigation of its geological setting, the exploration of the regional hydrogeological setting and the primary underground excavations are all considered to be part of the siting process.

1.4 Structure

The document begins with a statement of the two primary protection objectives (Chapter 2). The system of confinement, multi barrier approach and system performance assessment are also described (Chapter 3). Repository siting is introduced and discussed along with the siting process and the role of criteria in this process (Chapter 4). The design of the repository system is described as well as the interrelationships between system components (Chapter 5). The discussion of repository construction includes constraints and confirmation studies (Chapter 6), and the report closes with a summary and conclusions (Chapter 7). The key item to note from this summary is the iterative nature of the siting, design and construction processes.

2. PROTECTION OBJECTIVES

The primary goals or protection objectives of radioactive waste disposal are expressed by the IAEA [11] as two basic safety principles. These safety principles are: (1) responsibility to future generations and (2) radiological safety. The responsibility to future generations is to isolate high level waste from man's environment over long time scales without relying on future generations to maintain the integrity of the disposal system, or imposing upon them significant constraints due to the existence of the repository. The objective to maintain radiological safety is to ensure the long term radiological protection of man and the environment in accordance with current internationally agreed radiation protection principles. General guidance, in the form of safety principles, to meet these two objectives has also been formulated [11].

To meet the protection objective concerning responsibility to future generations, it is recommended that the burden on future generations be minimized by safely disposing of high level radioactive wastes at an appropriate time, technical, social and economic factors being taken into account. The post closure safety of a high level nuclear waste repository should not rely on active monitoring, surveillance or other active institutional controls or remedial actions. Furthermore, the degree of isolation shall be such that there are no predictable future risks to human health or the environment that are not acceptable today. Finally, protection of populations outside of national borders should comply with international standards.

To meet the protection objective related to radiological safety, it is recommended that for gradual releases from the repository, the predicted annual dose to individuals of the critical group should be less than the dose upper bound apportioned by national authorities from the relevant individual dose limit which currently corresponds to an annual average dose value of 1 mSv for prolonged exposures [1,2].

The dose upper bound that serves as the design constraint for the repository should therefore be established taking account of doses from global, regional and other local sources, and reserving a prudent fraction of the dose limit for potential future sources, e.g. future practices involving radiation exposure such as future uses of nuclear energy and other nuclear technologies.

For releases arising from a disruptive event, it is recommended that the predicted risk of a health effect should be less than a risk upper bound apportioned by national authorities from an individual limit of risk of health effects of one in one hundred thousand per year. Furthermore, it is recommended that radiation exposures resulting from the disposal of high level waste shall be as low as reasonably achievable, taking into account economic and societal factors.

The IAEA's safety principles as well as several of the protection goals set explicitly by national authorities do not mention a time limit for dose comparison or dose limitation. Some national authorities consider a cut off for judging radiation effects by dose comparison or total releases after approximately 10,000 years for several reasons. For example, they question whether a dose calculation on the basis of a biopath model, taking into account present eating and drinking habits, yields meaningful values when the extrapolation is pushed far into the future. Also, after approximately 10,000 years, the remaining radionuclide concentration in a repository will be near that of a naturally occurring uranium deposit.

3. SYSTEM PERFORMANCE

The system of confinement for high-level wastes is comprised of the waste form, container, sealing systems, backfill, seals, repository structure, host rock, and surrounding geologic formations. As stated in [11] the long term safety of high level radioactive waste disposal shall be based on the multi barrier concept, and shall be assessed on the basis of the performance of the disposal system as a whole. The concept of multi barrier confinement is based on using both natural and engineered components of the site and repository system to prevent or delay migration of the radionuclides from the waste through the geosphere to ensure that the protection objectives in Chapter 2 are met for the time period established by the national authorities or during which the radiotoxicity may have harmful effects on individuals.

The multi barrier approach provides defense-in-depth because the performance of the confinement system does not rest on a single component or barrier but rather on the combined performance of several barriers with built-in redundancy. Any single component or barrier is relied upon to a varying degree for the safety of the confinement system so that the safety of the total system will not be compromised by the failure of any one barrier. If, relative to the base case prediction, a single component or barrier does not fully perform its intended safety function, the overall confinement system must be more than sufficient to meet the protection objectives.

Total system performance assessments will be used to determine the safety of repository concepts and designs [7]. These assessments may include definitions of the expected performance of both the engineered and natural barriers beyond those given in Chapter 3. Uncertainties regarding the performance of each of these barriers increases with time, e.g. extrapolation of data supporting the performance of engineered barriers becomes less tenable as the period of prediction increases and some environmental and geological processes and events cannot be precisely predicted. Total system performance assessment will, to varying degrees depending on the host rock and the repository design concept, establish the degree of confidence for both the engineered and natural barriers. Performance models should take into account possible mechanisms through which the engineered barriers may limit the rate of radionuclide release into the natural barrier. These mechanisms could include slow dissolution of the waste form and physical and chemical control of the environment between the waste form and the natural barrier. In most settings, the natural barrier will be the last in a sequence of barriers into which the radionuclides will pass. The natural barrier will also present the longest pathway through which the radionuclides will have to pass to reach man and his environment.

In order to enhance confidence in meeting the overall system safety objectives, national authorities may specify subsystem performance objectives for individual components or barriers. Performance of those individual components or barriers against the subsystem performance objectives should be evaluated within the context of their contribution to the safety of the overall system.

Generally, generic or universal criteria cannot be established for the subsystem performance objectives or the relative reliance placed on the different components or barriers in the confinement system. Such performance criteria will depend on the site specific conditions, including the characteristics of the waste form, the chosen container material, the repository and waste package designs, the construction method, the emplacement method, sealing systems, and repository closure method. Preliminary performance criteria should be established for individual components or barriers early in the development of the repository design. These criteria may need to be re-evaluated as additional information and analyses concerning the design and performance of the confinement system are developed during site characterization, design, construction, and operation of the repository. Performance assessment of the individual components or barriers is, therefore, an iterative process. Thus, where allocations of performance to the individual components or barriers are made, these might be expected to evolve as increased understanding of the overall system performance evolves.

It is recognized that the evaluation of the long term performance of the confinement system must be based in large part on estimates provided by predictive modelling because no long term performance histories for similar facilities exist. Compliance of the confinement system with the protection objectives can be supported by safety assessments based on verified models that have gone through an appropriate validation process to the extent realistically achievable. Consequently, it is very important to incorporate appropriate experimental and assessment activities during site characterization, design, construction, and operation. Pre-closure monitoring of the repository to provide sufficient information for validation of models and confirmation of the short term performance of individual components or barriers in the confinement system is also essential. Natural analogue studies of relevant processes may be used to support extrapolation of long term performance from short duration experiments, to support the validation of models and eventually to enhance confidence in the safety assessments.

The assessment of the performance of both the total confinement system and its subsystems should include not only the current site conditions, as defined during site characterization, but should also consider: (a) changes in site conditions that may be reasonably expected to result from the construction and operation of the repository, (b) changes in site conditions that may be reasonably anticipated to occur due to natural processes and events during the period to be assessed, and (c) changes in site conditions that may result from credible disruptive scenarios (natural or human induced) that can be reasonably postulated to occur during the period to be assessed.

4. SITING

4.1 Introduction and background

The main objective of a repository is to achieve the desired degree of safety for the final disposal of the waste [14]. Hence, the information gathered during the selection and screening processes and later the data collected during exploration should be directed primarily towards providing information that is relevant from the safety point of view. Because the safety assessment is performed mainly using analytical tools, this means focusing the geological, hydrogeological and hydrogeochemical investigations on establishing a consistent input data set for the crucial model input parameters.

The protection objectives of the repository system are met by the engineered (i.e. man made) safety barriers and the geological environment hosting the repository. Whereas the man made components of the repository can be engineered to provide the necessary safety and redundancy, the geological situation (natural barriers) is provided by nature and cannot be deliberately altered. Hence, a favorable geological situation is essential. The process of siting involves selecting, using appropriate technical and social criteria, characterizing the natural barriers, and finally confirming the suitability of the repository site [8].

The natural barriers are comprised of those natural characteristics or properties of the geosphere, primarily geological, hydrogeological, and geochemical, that contribute to confinement of the radioactive wastes within the engineered barrier system and the geosphere by preventing or delaying the migration of radionuclides from the emplaced radioactive wastes. The natural barriers include not only the immediate volume of rock in which the repository is excavated, but also the surrounding rocks. Potential pathways exist in nature for the migration of radionuclides to the biosphere. The predominant mechanism for release of radionuclides from the repository is groundwater flow. Vapor phase and gas phenomena may also be important and should also be evaluated.

The natural barriers contribute to confinement in a multitude of ways. Desirable attributes of natural barriers include: sufficient depth of burial, adequate lateral extent of the host rock, long groundwater residence time, limited groundwater flux through the repository, favourable groundwater chemistry, and conditions that are favourable to the retardation of dissolved radionuclides along groundwater flow paths [9].

Key components of the natural barriers, therefore, are:

(1) the geologic framework of the host rock;

(2) the surrounding geological formations (which may include potential pathways via porous media, faults, fractures, or shear zones for groundwater flow and radionuclide transport);

(3) the hydrological properties of the host rock (e.g., hydraulic conductivity, groundwater flux through the repository, and direction and gradient of groundwater flow);

(4) the chemistry of the groundwater (e.g., pH, Eh, dissolved solids and colloids); and

(5) the geochemistry of exposed and/or altered mineral surfaces along groundwater flow paths (e.g., retardation factor).

The natural characteristics or properties of the geosphere should be determined by site characterization and confirmed by performance assessment testing during repository construction and operation. The safety assessment should identify the natural processes and events that have created the current site conditions and should also identify the credible, natural or human induced, disruptive scenarios that may be reasonably postulated. In support of the performance assessments described in Chapter 3, the site and regional characterization should also establish the value or range of values for the natural characteristics or properties not only under natural conditions [15] but also as affected by (a) the construction of the repository or the emplaced wastes, (b) the occurrence of the reasonably anticipated natural processes and events during the period to be assessed, and (c) the occurrence of the credible, natural or human induced, disruptive scenarios during the period to be assessed. These performance assessments will demonstrate the estimated short term and long term effectiveness of the natural barriers and will support the iterative process of design and performance optimization of the repository system (see Chapter 5).

Various nations developed different concepts of geological waste disposal. These differences result from differing technical and social perspectives in the respective countries and in no way represent a classification of the repository concepts from the safety point of view.

National experts have discussed the question of whether some host rock options are inherently preferable to others [16]. The diversity of potentially suitable geological environments and the need to adapt repository designs to specific site conditions may result in apparent differences in the disposal systems, without negatively affecting the levels of safety of the respective repositories. This report [16] expressed no preferences (from the safety point of view) for one host rock over others.

Similar considerations apply to site selection. Potentially suitable sites for the repositories for high level and long lived waste have already been identified in a number of countries, in several types of host rock formations and geological environments. The selection of an actual host rock and a repository site will depend on both technical and non technical factors. It is important however, to ensure that the technically based safety objectives are respected regardless of other non technical considerations. These objectives thus become necessary but not sufficient constraints on siting.

Criteria have been developed against which the performance of a site can be measured [11]. In principle, one could therefore attempt to select the "safest" site. In practice, however, it may not be necessary and is often not possible to distinguish between sites solely on the basis of such criteria [16]. Specific properties of the host medium might differ at several sites but each of them would be capable of successfully isolating the waste, thus meeting the safety requirements. Other factors, e.g., the transportation situation or institutional considerations could also be important in determining which site is appropriate.

4.2 Siting process

There are two general approaches to selecting repository sites. The traditional one seeks to select an optimal site via a progressive screening and selection process in which all potential sites are evaluated against a list of technical criteria. The less favourable sites are eliminated and a short list of potential candidates are subjected to more detailed evaluation programmes. Ultimately, a single site is selected which maximizes the isolation and containment potential for the wastes [13].

While some countries have found this to be the preferred method, others have encountered institutional pressures for and against specific sites which are independent of this traditional technical approach. A local community or political entity may not care that theirs is the optimal site and may vigorously resist its use. In order to minimize public opposition to sites, a second general approach is evolving which relies on either communities voluntarily offering a potential site or a specific site being selected for institutional reasons. However, these sites must be carefully studied to determine whether they have the necessary technical attributes to ensure safety. Decision makers require assessment methods and site acceptance criteria which ensure that no technically unacceptable sites remain as candidates even though the institutional constraints are favourable. Regulators may need to establish realistic minimum criteria rather than optimistic or idealized criteria based on the assumption that somewhere in the country a site can be found to comply. The form of criteria developed will reflect national differences in geological settings and regulatory structures. Furthermore, it is appropriate to develop these criteria at the earliest stage of the repository development process and to maintain the criteria as constant as possible so that both the public and the technical evaluators know where they stand at each subsequent stage. Early availability of criteria will also help focus the technical evaluation onto the most critical components of the natural and engineered systems with respect to each criterion.

The stepwise approach described below represents an idealized approach and is only intended to serve as a general guide for developing national programmes. In the beginning of the siting process, more general information will be collected than will be needed for subsequent detailed studies. In addition, an appropriate conceptual model of a site cannot be established until a reasonably comprehensive understanding of the site specific geological setting has been achieved. Later, the siting process becomes iterative and a better understanding of the site leads to a more appropriate model, which allows specification of those parameters that must be investigated in greater detail. At some point, characterization of the site is considered sufficient and the programme moves on to construction of the repository. The decision as to when this iterative process of characterization and modelling ends depends largely on judgement by the implementing organization and the national regulatory authorities.

In the technical investigative process, the relative effort expended on each step may vary greatly depending on the quantities of waste, the geological environment, the host rocks, the regulatory environment and other considerations. The principal steps are:

(1) Planning and general studies
(2) Area survey
(3) Preliminary site selection
(4) Site characterization
(5) Site confirmation

At each step of the process, integration is required among the earth science investigations and concurrently evolving analyses of radionuclide transport and safety and further development of the repository concept. As investigations proceed, the studies usually progress from the general to the specific. As the studies become more specific, more field or experimental data are needed and are used as a basis for the technical evaluations.

Much valuable information can be obtained about a potential site during the early phases of site investigation without penetrating the ground. However, penetration into the host rock by drilling is required before one can have confidence in the interpretation of the studies made at the surface and in order to obtain data by in situ measurements. Indeed, even better information is obtained during construction and later stages of the repository operations, when man himself enters the geological environment to allow more extensive use of his investigative techniques. Judgment however, will be needed to balance the benefits of multiple penetrations (i.e. drill holes) and extensive excavations, which optimize the understanding of the site, and the possible adverse effects on site performance resulting from these penetrations. Borings and excavations should be placed to minimize short circuits between the repository zone and the biosphere which in turn might adversely affect site performance.

The initial planning requires coordination of many disciplines, and a general knowledge of the kind of information needed and the scientific techniques available to obtain that information. These activities must integrate input from earth science, management, nuclear and engineering experts to take into account the quantities and characteristics of the wastes to be disposed of, the location of major waste sources, the possible concepts for repository design, and the timing needs for a repository.

On the basis of a general knowledge of the geology and hydrogeology of the country, as well as radiation protection and safety analysis principles, selections can be made of nationally acceptable repository safety principles (see for example, [11]), waste confinement concepts and site selection factors. Information required for assessing the performance of the proposed barriers can then be identified.

Site selection factors should be reviewed and priorities assigned. From this review, including an examination of basic earth science data, potential host rock types can be identified. Criteria are developed for selection of areas of potential interest. Safety analysis methodologies are reviewed and basic methods selected and applied on a generic basis to identify the important parameters for which data will be needed [10].

The area survey stage provides the reconnaisance information on the geological characteristics within a country that are needed to select general areas that may contain suitable locations for a repository site. This selection is made by comparing geological conditions (including the availability of potential host rocks) and other factors with the general site selection factors.

Generally, as a first step, an inventory of areas of interest is developed. A common approach is to delineate areas that contain potentially suitable types of host rocks. The inventory provides the basis for selecting promising or research areas by comparison with area selection criteria. The comparison should consider existing data on significant features such as major faults, extensive fracture zones and mines.

Also included at this stage is a review of pathway and safety analyses. Using the known characteristics of the areas and potential host rocks, a preliminary safety analysis may be performed to provide guidance for activities in the next stage. Based on these and on geological investigations performed to date, criteria are developed for selecting preliminary sites for more detailed evaluation. The techniques to be used for the subsequent more detailed site investigations are also selected.

At the stage of preliminary site selection, the areas are reduced to likely sites(s) for detailed investigations. Relatively extensive field work is performed for the first time; potential host rocks and geological and hydrogeological conditions are characterized on a broad basis. This stage may be performed as several steps.

In parallel with the site investigation, preliminary repository designs, preliminary safety assessments, social, economic, environmental and transportation studies are prepared for an integrated evaluation of the site. All these evaluations are then assessed in relation to objectives and criteria established earlier to provide for selection of the final host rock formation(s) and site(s) for characterization.

Detailed investigations are undertaken at the site characterization stage to confirm the results of the previous investigations and to confirm the suitability of the selected host rock and site for a repository. Additional borehole investigations and/or perhaps underground exploratory facilities will be needed to obtain a more fully detailed definition of the hydrogeological, geological, geotechnical and geochemical conditions at the site. This information will also provide a basis for further refining the repository design and the safety analyses.

Because a very substantial increase in scale of effort and expenditure is necessary for construction of the repository, it is appropriate to document and evaluate in depth the appropriate information required to establish firm bases for this decision. As a basis for the repository design work, information is also required about the conditions prevailing at the working depth for the facility. A balance must be struck between the desire for detailed data and the need to limit perforations in the rocks. The final information for the layout of the repository and the safety evaluations will be obtained from investigations undertaken at the repository depth. The repository design may be directed towards modular elements that can be adapted to conditions found at the depth to be used for the repository.

The information obtained during the total site investigation programme is continually used to revise the radionuclide pathway analysis by adapting it to the specific characteristics of the site and its surroundings. The site specific data are then combined with other safety related data into an updated detailed safety analysis for the planned repository. This safety analysis should consider, at an appropriate level of detail, the forecast of the future performance of the repository. The results of the safety analysis are then used in the assessment of the site's suitability, in the decision to begin construction, and in the identification of parameters to monitor and confirm the post closure performance of the repository. Further confirmatory investigations during construction will probably be required for a decision to commence operation and/or closure.

Investigations should continue during the operational phase of the repository, including its closure and sealing, and until full assurance is obtained that the repository may be safely decommissioned. If the studies at any stage do not confirm the suitability of the site, the repository site may have to be disqualified and other sites selected and investigated using the same procedures.

4.3 Role of criteria

Siting includes all activities leading to the acceptance of a suitable site for a repository. Decisions made during this process are typically based on safety principles and technical criteria including those enumerated in Chapter 2. The following discussion illustrates how these criteria, as well as other non technical criteria, can be used as a quantitative basis for decisions made during the site selection process.

Safety principles and technical criteria can provide a basis for decisions during the area survey and preliminary site selection process. If a formal technical process for site screening is adopted, it is possible to develop screening criteria that reflect institutional and radiologic safety concerns. These criteria can be developed to provide a quantitative basis for comparative evaluations of the relative suitability of the various site options.

The safety principles and technical criteria should also provide a basis for guiding the programme of site characterization. The main objective of the site characterization programme is confirmation of the suitability of the site by:

(a) developing a description and understanding of the present geological, hydrogeological, geochemical and geomechanical characteristics of the site;

(b) predicting the long term dynamic evolution or changes of the characteristics of the site due to, for example, tectonic, climatic or erosion scenarios;

(c) predicting geological, hydrogeological, geomechanical, geochemical and other environmental responses of the site to construction, operation and closure of the facility;

(d) determining the actual hydrogeological, hydrochemical and other environmental responses at the site due to construction, operation and closure of the facility;

(e) developing and confirming the engineering design of an underground facility that will provide a safe environment during disposal operations and following closure of the facility;

(f) defining the waste package environment;

(g) validating components of models and assessing the long term safety performance of the facility following closure in comparison to regulatory safety criteria [5].

The technical criteria are developed as a means to demonstrate compliance with the safety principles. Accordingly, they provide a quantitative description of the approach to demonstrate the suitability of the site which in turn provides a description of the information to be obtained by the site characterization programme. As information becomes available from site characterization, it can be used to make continuing assessments of the suitability of the site and the validity of the models as well as to redirect the site characterization programme, should the evolving models so dictate. The bases for these iterative evaluations of site suitability and the information needed from site characterization are derived from the safety principles and the technical criteria.

In summary, the safety principles and technical criteria describe an approach to evaluating site suitability. They also provide guidance for identifying appropriate tests that form the basis for a programme of performance confirmation. A performance confirmation programme should be started during site characterization and will provide assurance that the predicted site character and suitability are borne out by further evidence encountered during construction of the repository. The basis for a performance confirmation programme is derived from the arguments for site suitability, which are based upon safety principles and technical criteria.

5. DESIGN OF THE REPOSITORY SYSTEM

5.1 General

The prime objective of the design of a repository is to limit the concentration of radionuclides in the environment to permissible levels. Facilities and equipment must be provided that will permit handling and emplacement of waste in the repository so that the requirements established by the national authorities for protecting workers, the public and the environment are respected both during normal operating conditions and also in the event of accidents. The design should take into account all stages of repository life, including construction, commissioning, operation and decommissioning [14].

Since the components of the repository system act together in providing safety related functions, all components must be selected and/or designed to meet specific functional requirements that must be established for a total system [3]. In addition, the design must be in accordance with all appropriate regulations and should allow for inspections, tests and maintenance programmes.

Because the geological environment will be different for each repository and the engineering concepts for each repository may also be different, site specific repository system safety analyses should form the basis for establishing detailed design criteria. Additionally, other aspects such as social, environmental and economic considerations may be taken into account to the degree defined by the national authorities.

The development of the repository system design should be an iterative process beginning with a first generic approach and proceeding eventually to a licensed site and repository. The initial very general design criteria are based on the overall national waste disposal strategy. They take into account the types and quantities of waste, the available repository medium and surrounding formations, the protection objective and other regulatory requirements specified by the national authorities. Designs of repository systems developed at this stage can only be conceptual, limited as they are by lack of site specific information. However, sensitivity studies of the performance of conceptual repository systems to a variety of assumed geological conditions can assist in identifying information needed from site characterization and from research and development programmes into waste form, waste package and repository engineering.

As site characterization proceeds and an understanding of the site specific geological conditions is obtained, the functional requirements for individual components of the repository system should be reviewed and specific design criteria developed that are adapted to local site characteristics and to special design features which take advantage of those site characteristics. This will lead to modification of the repository system design taking into account the new understanding and the reassessment of the overall safety of the repository system.

This iterative process may identify situations where the design of engineered components of the repository system needs to be modified to be compatible with site conditions, or can be optimized without detriment to safety related functions.

5.2 System components

A waste disposal system consists of a number of components which can be grouped together in a variety of ways. Taken together the overall system must provide the required degree of protection to humans and the environment from the potential harmful effects of the radioactive waste.

In performing safety assessments, the system is often divided into subsystems representing the immediate vicinity of the emplaced waste (near field), the more distant geological setting (far field/geosphere) and the environmental exposure pathways (biosphere). For the purpose of this document, it is useful to further subdivide the near field into the following components:

- waste form
- container
- emplacement environment
- repository
- repository sealing systems

A combined evaluation of the conceptual design and safety analyses should lead to an updated design of a repository at a selected site. Since safety of the repository facilities can be achieved with different combinations of engineered and/or natural barriers, there is considerable room for optimization of the individual components or elements of the system. For instance, a wide variety of combinations of container material and container thickness could provide the same container lifetime in combination with different waste forms and emplacement conditions. There is also room for the intentional use of redundancy to increase safety factors and thus to increase confidence in system performance.

The analysis of how the repository functions over a long period of time requires characterization of the various components of the repository system (data) and description of the interaction that can occur between the components of the repository system and the disposal site (models). Both data and models must however, be relevant for all the reasonably possible conditions to which the repository may be subjected (scenarios). Finally, the prediction of repository performance must be expressed in terms that are compatible with the criteria of the national regulatory standards [4].

Returning to the sub-components of the system, the five in the above list can be termed the engineered barriers. These are the man made structures and systems which are added to the underground openings and disturbed rocks and to the waste itself to reduce the flow of water to the waste and delay the return of the nuclides to the geosphere. These engineered barriers differ from the natural ones because they can be specified, manufactured and controlled to meet particular performance needs whereas the natural barriers are only available within the constraints of site selection. Each of these engineered barriers or sub components are described below.

5.2.1. Waste form

The nature of the waste forms determines the design of the handling equipment for the operational phase and provides the source term inventory for safety analyses of the repository system. The prime role of the waste matrix is to constrain the release of radionuclides by virtue of its slow degradation. Key parameters are the rate of degradation (physical and chemical) of the matrix and the maintenance of the distribution of radionuclides within this matrix. Stability is required over long periods of time. A mechanistic understanding of degradation processes is necessary to support improved long term modelling approaches. For high level waste, the matrix for instance can be borosilicate glass although a number of alternative waste forms are being evaluated. For spent fuel the uranium oxide itself becomes the waste form.

Waste forms, whether spent fuel or the immobilized waste from reprocessed fuel, should be inert and have low solubility. As long as groundwater is prevented from coming into contact with the waste, no dissolution of the radionuclides will take place. In the case of a design for a repository the process of dissolution when the waste comes in contact with water should be modelled to give the necessary release rate data. The safety function of the waste form is fulfilled as long as the actual release rate following container failure does not exceed the release rate postulated in the safety assessment.

When the waste comes in contact with groundwater, a leaching process begins. The radionuclides are leached from the waste form and discharged into the groundwater. The leach rate is determined, for instance, by the properties of the waste, the water flow rate and the chemical conditions in the near field as well as the ambient temperature and radiolysis phenomena caused by the waste. The influence of products arising from matrix degradation (dissolution, radiolysis, biodegradation) may need to be assessed as they may change the physical and chemical environment in the near field and thus alter the migration rate of the radionuclides.

5.2.2 Container

The waste container provides physical isolation of the waste form for a limited time as well as a convenient medium for handling and placement of the waste during disposal operations. It is also likely to carry an identifier which relates to its contents and origin. As long as the container is intact, confinement will be total and the safety function of the container is fulfilled.

The period over which the container remains intact is influenced by type and thickness of the container material and the chemical and physical conditions in the near field and the chemical composition of the water in contact with the container. These factors can be controlled by a suitable design of the container and the repository which may include sorbing or precipitative substances, and other chemical conditioning of the near field.

The container has the important role of contributing to the physical confinement of the waste. The contribution this makes to safety can vary considerably. For example the control of short lived, mobile radionuclides may be total if their half lives are a small fraction of the container life expectancy. The container is one of the barriers of the total isolation system which can be designed to make a very specific contribution to safety. It may also function as a storage and transport container if the design and construction are suitable. Even after the container is breached, it may beneficially influence the chemical conditions in the near field. Hence the design and development of a range of standard containers requires thorough specification, design study, research and development culminating in comprehensive prototype proving demonstrations.

5.2.3 Emplacement environment

The waste emplacement environment includes any opening excavated specifically to hold the waste container, and, materials placed around the container (buffer material). The physical and chemical conditions that are anticipated to develop in the opening or the buffer zone subsequent to emplacement must also be evaluated [5].

Buffer material may be used to fulfill a number of safety related functions. These include:

- filling the voids, and restoring host rock integrity;
- providing physical support between the containers and the walls of the excavated chamber;
- limiting the rate of migration of groundwater to the surface of the waste container; and
- limiting the rate of migration of radionuclides from a breached container.

The design of the waste emplacement environment should take into account the effects of the waste heat and radiolysis on the buffer material and the adjacent rock.

5.2.4 Repository

In order that all the radioactive waste arriving at the repository can be disposed of safely, a number of operations have to be carried out, from waste reception and final conditioning to emplacement of the waste package in the final disposal location and sealing it in.

Services required at a repository include ventilation, power, storage and the emergency systems necessary at all underground facilities. Decontamination areas for monitoring and cleaning transport vehicles and handling any damaged waste packages, seal material preparation plant, and all the office and parking areas associated with modern industrial operations, will also be required. In this report the emphasis is placed on the excavated openings that form the waste emplacement rooms of the facility and on the associated access ways [14].

In most radioactive waste storage programmes, it is not expected that waste should be retrieved from a repository and provisions for retrieval will not normally be required in the design. However, should waste retrieval be a design requirement, it should not compromise repository system safety.

The design of the underground facilities is an adaptation of the natural rock structure and just as the rock structure is in a state of very long term evolution it should be remembered that the repository design also evolves through the stages of desk studies, ground investigations, shaft sinking and emplacement room excavation. Mining engineering has been developed over centuries. Experience has shown that a flexible approach is required so that design iterations can take account of experience gained from construction and operations [10].

All the design options in any of the host formations must achieve the isolation standards set by the national regulatory body for the particular wastes to be emplaced in the repository. This is the primary requirement. Beyond that, the design should be based on standard practices to provide the wide range of services like ventilation, transport, etc., necessary for what is essentially a large, underground processing operation with high control standards. All service equipment should be well proven, reliable and robust. Additionally, the higher risks associated with machinery used in underground operations necessitates the provision of standby and emergency equipment. Special consideration is required not only to limit exposure to operators from the radioactive packages, but also to limit the spread of radioactive contamination in the event of an accidental spillage, particularly in the access passages with high ventilation air flows.

The design must provide for orderly waste emplacement, and reliable emplacement records suitable for verification by independent inspectors. The arrays of waste containers should optimize the use of space in the repository, allow for the emplacement of appropriate sealants, and ensure any fissile material remains in a subcritical configuration. Provision must be made to backfill and seal access ways and emplacement rooms.

5.2.5 Repository sealing systems

Repository sealing systems are those engineered barriers that will be included in repository designs to help control water flow and radionuclide release from the repository system. They may achieve these goals by physical, chemical or physico chemical actions and are likely to be used in both the near and far fields. The sealing system may include the following: buffers, backfills, bulkheads, dams, grouts, etc. [15].

The nature of the host medium will largely dictate repository and associated seal function and design. A range of seal design concepts is needed to accommodate the different waste forms and the hydrogeological conditions encountered in different host media. Design concepts will also reflect the way sealing structures and measures are needed to control groundwater flux and radionuclide migration in and around the repository during the construction, operating and post closure phases.

The design life of each seal will depend on its intended function and the materials selected for seal construction must reflect that condition. Using available engineering experience, it is possible to design dams and other structures that are only required to function for the limited operating period of the repository. When seals are required to function for much longer periods, it will be necessary to provide convincing evidence for their longevity. This will be more critical if credit is taken for the function of these seals in total repository performance assessments [7].

Four main methods may be used to assure long term seal performance. These are examination of geological evidence, examination of archaeological evidence, accelerated laboratory and "in situ" testing and the application of theoretical models. The use of only one of these methods is unlikely to satisfy national authorities regarding long term seal performance. For those repository designs which demand very long term seal performance, IAEA [15] indicates that in addition to spoil material from the host rock, cement , clay and bitumen based materials are the most likely to provide the necessary performance.

In common with overall repository design and established geotechnical engineering practice, approaches to seal design must reflect the increased understanding of the repository system gained as shaft excavation, disposal area development and waste emplacement progressively proceed. Preliminary concepts for seals developed prior to penetration of the host medium should be refined to account for the geological and hydrogeological features encountered. The performance of sealing systems developed through this process may need to be further qualified through "in situ" testing and subsequent monitoring.

The principal function of the seal is to restore as far as possible the host rock integrity and prevent release of radionuclides from the repository. On no account should this principal function be compromised by accommodation of other factors including the possibility of waste retrieval. These factors may be built into the designs if they do not influence the principal function. If possible the seals, particularly those between the disposal areas and the surface may need to be designed to resist inadvertent intrusion and may include appropriate hazard warning measures if required by the national authorities.

5.2.6 Geosphere

Components in the geosphere system are the host rock and the controlling hydrogeological features. If radioactive materials leave the near field, any further transport will take place under conditions existing naturally in the bedrock. These conditions differ for various types of bedrock and are specific to each site.

In a fractured rock, sorption and precipitation on fracture surfaces, as well as dispersion and diffusion of radionuclides into the rock matrix, are influenced to varying degrees by differing rock properties, including the characteristics of the fracture system, fracture filling minerals, porosity, hydraulic conductivity, etc. Many substances are likely to be retarded to some degree along the way so that the travel time for some radionuclides will be longer than for water.

In a rock such as salt, which is free of mobile groundwater, there are no water filled pores which could provide a pathway for transport of dissolved radionuclides. Even if the formations today are free of groundwater, future events which can change this situation should be considered. The repository area could be totally or partly saturated due to natural processes, deterioration of shaft seals or by human intrusion. Modelling of water flow should take into consideration the water density effects which can be essential for the flow.

5.2.7 Biosphere

Components for consideration in the biosphere system are the regional and global ecosystems. If and when radioactive materials from the repository reach the biosphere, they may be incorporated in different food chains, where they may be either concentrated or diluted. How much finally reaches man depends on the natural conditions of the pathways and man's relationship with nature.

The nuclides can be transported as solids, liquids or gases. The design must ensure that the transport of the radionuclides to the biosphere in any of these states is within the regulatory requirements.

6. CONSTRAINTS ON CONSTRUCTION

6.1 General

The construction period covers the time up to the commissioning of the repository and start of the operation period. The goal for the construction work is to provide the needed facilities and repository capacity. The techniques used for repository construction must be selected to limit deterioration of the site performance resulting from construction.

Specifications for construction can be developed based upon constraints identified by the safety assessment of the construction work. These should be incorporated in a formalized construction programme. In addition to the requirements for the construction work, methods for verification of the design and the construction techniques should be included in the construction programme.

There should also be a separate programme of confirmation covering the site investigation activities that continue concurrently with construction, as it will be necessary to identify the changes in the natural conditions of the site during excavation of the tunnels and caverns. Based upon this investigation programme, the predicted changes in the geomechanical, hydrogeological and geochemical conditions of the site can be checked throughout the construction period. The goal is to demonstrate that the actual conditions and any deviation from those assumed for the preliminary safety assessment will be identified and considered in the final safety evaluation of the site [13].

At the end of the construction phase a safety assessment should be performed based on data and experience obtained during construction. This assessment can then be the basis for the monitoring programme during the operational phase and should be performed prior to commencement of operation of the facility according to relevant national policies.

6.2 Construction programme

The construction programme should not only include the working documents and a conventional quality assurance programme, but should also preferably include the constraints on construction work identified in the performance assessments during the design phase as well as a programme of performance monitoring to confirm the results of site characterization, the impacts of construction on the performance, and the results of modeling. These are considerations comparable to those associated with operation and closure of the repository.

For example, in most repository concepts for geological disposal, it is essential to understand the effect of the stress disturbed zone around access tunnels or shafts. Due to changes in the stress field, the hydraulic conductivity may change along the tunnels and shafts and the stress disturbed zone may permit an increased waterflow around the access tunnel or shaft. This potential problem must be considered during the design of the repository and sealing methods that will be identified for the repository. This may be particularly important where shafts could provide pathways to overlying aquifers.

The construction programme should also include activities dealing with confirmation of the design and the impact of the construction techniques. Tests should be performed during the construction phase in order to verify that the final designs of tunnels, shafts and other structures are in accordance with the specifications. All activities and results of tests in the construction programme should be carefully documented [14].

6.3 Site investigations during construction

The programme for site investigation during construction depends on the repository design concept, the completeness and sufficiency of site characterization data obtained before start of repository construction, and plans for further monitoring and confirmation.

The design of the disposal accesses and chambers should be given sufficient flexibility to meet known variations in the near field host rock. The characterization programme to be used during construction should include necessary investigations and criteria for the evaluation and selection of emplacement areas. Some parts of the host rock might, in fact, be abandoned due to unacceptable properties.

The programme for site investigations during the construction phase should be designed to collect those data identified as important to the total system safety analyses. Examples of site data include:

- Physical and chemical properties of the host rock
- Geomechanical conditions in the host rock
- Groundwater flow paths
- Groundwater chemistry

These data should be collected, evaluated and compared with data used in the safety analyses. Reassessment may be necessary during this phase in order to confirm that the properties of the host rock are within the limits of the safety analyses.

6.4 Site confirmation and safety report

All activities and data collected from investigations during the construction period should be carefully documented; databases for this purpose are being developed in many countries.

At the end of the construction phase, an updated total safety assessment should be performed on the basis of data and experience obtained during construction. The result of this safety assessment can then be used to identify the need for various investigations in the pre closure monitoring programme which will be carried out during the operating period. This safety report will be the final assessment of the site and the design of the repository prior to the commencement of disposal activities according to the relevant national policies [4].

7. SUMMARY AND CONCLUSIONS

The siting, design and construction of a deep geological repository for the disposal of high level and alpha bearing wastes is a major long term project involving many disciplines. The prime safety requirement is to satisfy the protection objectives. These objectives can only be achieved by an iterative process drawing together more and more detailed information obtained as the project progresses through its various phases of investigation, construction, detailed design and performance assessment. By this process, the design is brought into balance with the characteristics of the chosen site.

The site selection process must be methodical and thorough because a deep repository is essentially a utilization of the inherent confinement properties of the chosen host rock. The preferred site must satisfy a balance of social, institutional, environmental and technical considerations. Since the geological properties are important to radiological safety, it is necessary to ensure a site has adequate long term isolation properties which contribute to a repository system satisfying the regulatory standards. The process needed to achieve this is set out in the report..

Finally the documentation for all the many processes and phases of the project must be systematically collated and recorded to ensure an accountable and open record is available of the information and logic on which the project was based.

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