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Procedures and techniques for closure of near surface disposal facilities for radioactive waste

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FOREWORD

Short lived low and intermediate level radioactive waste (LILW) is generally disposed of in near surface disposal facilities. The majority of the facilities are engineered trenches or vaults constructed below or above ground surface, while earthen trenches and rock caverns are also used, depending on site characteristics, regulatory requirements, and waste management policies, taking into account socio-economic conditions. Near surface disposal involves a series of sequential activities that include planning, siting, design, construction, operation, closure and post-closure controls.

A number of IAEA publications that have been issued, or are currently under preparation, address such issues as selection of technical options, establishment of implementation procedures, and assurance of quality for disposal activities, which take into consideration national and site-specific conditions, such as site characteristics, infrastructure and resources, socio-economic considerations, and regulatory requirements.

Repository closure is an important phase of the overall repository life cycle. Isolating the radioactivity and minimizing radiological risk to humans and the environment requires closure activities to be completely integrated with other aspects of the repository, including site characteristics, "as-built conditions", operational history, and other relevant technical issues. Another important aspect is that planning for closure needs to be performed in a timely fashion, especially for the currently operational repositories. For new repositories that are in various stages of development, integrating closure considerations into the design and operation can result in a significantly reduced level of effort and costs for repository development. Repositories that have already been closed may also benefit from some aspects of closure planning, such as institutional control during the post-closure period.

This report is intended to provide Member States with guidance in planning and implementation of closure of near surface repositories.

The report was developed with the help of consultants and an Advisory Group. K.W. Han and R. Dayal of the Division of Nuclear Fuel Cycle and Waste Technology were the responsible officers at the IAEA.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

The near surface disposal of low and intermediate level radioactive waste (LILW) has been practiced in a number of Member States for many years [1,2]. At present, there are many operational and shut down near surface disposal facilities in the world, as well as many new facilities that are in varying stages of development. These facilities include waste placed in excavated trenches, engineered vaults and rock caverns. Some of these facilities are no longer receiving waste and have entered the closure phase of their life.

Although near surface disposal facilities have been in operation in many Member States for a few decades, the extent of experience in performing closure of such facilities is limited at present. Compared with other aspects of radioactive waste disposal, there are comparatively few publications and guidance documents that address repository closure. With an increasing number of near surface repositories approaching their closure phase in the next decade or so, it is expected that Member States will require guidance on closure planning and implementation. This document is concerned with the closure phase of near surface repositories.

Closure of a disposal facility is the last major operational step in completing the disposal system. It is defined as a *systematic action that is conducted after the receipt of waste ceases and waste emplacement operations have been completed with the intention of providing a final configuration for the disposal system* [3]. Closure phase activities need to complement the design of the disposal system because the entire system is intended to isolate harmful constituents for a sufficiently long period so that risks posed to humans and ecosystems are acceptable [3]. Repository closure requires consideration of a combination of scientific, engineering, regulatory, and socio-economic factors that are integrated and optimized to select cost-effective alternatives acceptable to all interested parties. Some Member States already have experience in repository closure. However, there is a general need for information on the technical concepts and approaches for the planning and implementation of repository closure, especially in those Member States that are either planning for closure of currently operating facilities or developing new disposal facilities.

1.2. OBJECTIVES

The overall objective of this report is to provide Member States with guidance on planning and implementation of closure of near surface disposal facilities for low and intermediate level waste [4]. The specific objectives are to:

- review closure concepts, requirements, and components of closure systems;
- discuss issues and approaches to closure, including regulatory, economic, and technical aspects; and
- present major examples of closure techniques used and/or considered by Member States.

1.3. SCOPE

This report discusses mainly technical and some regulatory and socio-economic issues that need to be considered in the planning and implementation of repository closure. The information and concepts presented in this document apply equally well to formerly used and shut down LILW repositories and to current or planned repositories. A significant quantity of LILW presently resides in near surface repositories that were operational and shut down several years to decades ago. Closure of formerly used and shut down LILW repositories (i.e., legacy facilities) would usually be preceded by an analysis of remedial alternatives. Options for closing already shut down LILW disposal facilities are limited to measures that can be applied after waste operations have ceased such as capping, cut-off walls, *in-situ* stabilization or perhaps even complete removal of the wastes. In contrast, facilities that are in current use or planned for the future can incorporate additional features such as liners, leachate collection systems and drainage systems, in addition to caps and cut-off walls.

The various phases and activities associated with repository closure are illustrated in Figure 1. The contents of the report reflect the sequence of activities described in Figure 1. This document discusses closure systems and activities for sites where waste emplacement operations have ceased, including formerly used and shut down facilities and more recent facilities that incorporate elements of closure into their overall design. Some examples of closure experience from Member States are also presented (Appendix A), primarily related to formerly used and shut down LILW repositories and, specifically to capping as a closure option.

This report presents the views of experts within the international community on both operational and technical aspects of repository closure. As it relates to new facilities, many Member States have specific guidance from their respective regulatory authorities for closure of LILW disposal facilities.

1.4. STRUCTURE

The main body of the technical document is structured into five parts: Chapter 2, *Planning for Closure*, introduces the purpose of closure and outlines the technical, regulatory and public inputs that are integrated into a plan for repository closure. Chapter 3, *Analysis and System Selection*, describes the process for analysis of remedial alternatives for legacy facilities and provides an overview of qualitative and quantitative aspects of closure system analysis and design. Chapter 4, *Implementation and Confirmation*, provides a general description of issues pertaining to implementation of the closure plan, quality assurance and quality control, and the monitoring and surveillance activities that immediately follow repository closure. Chapter 5, *Summary and Conclusions*, provides a summary of the main themes covered in the preceding chapters, followed by an Appendix, describing closure practices in some Member States.

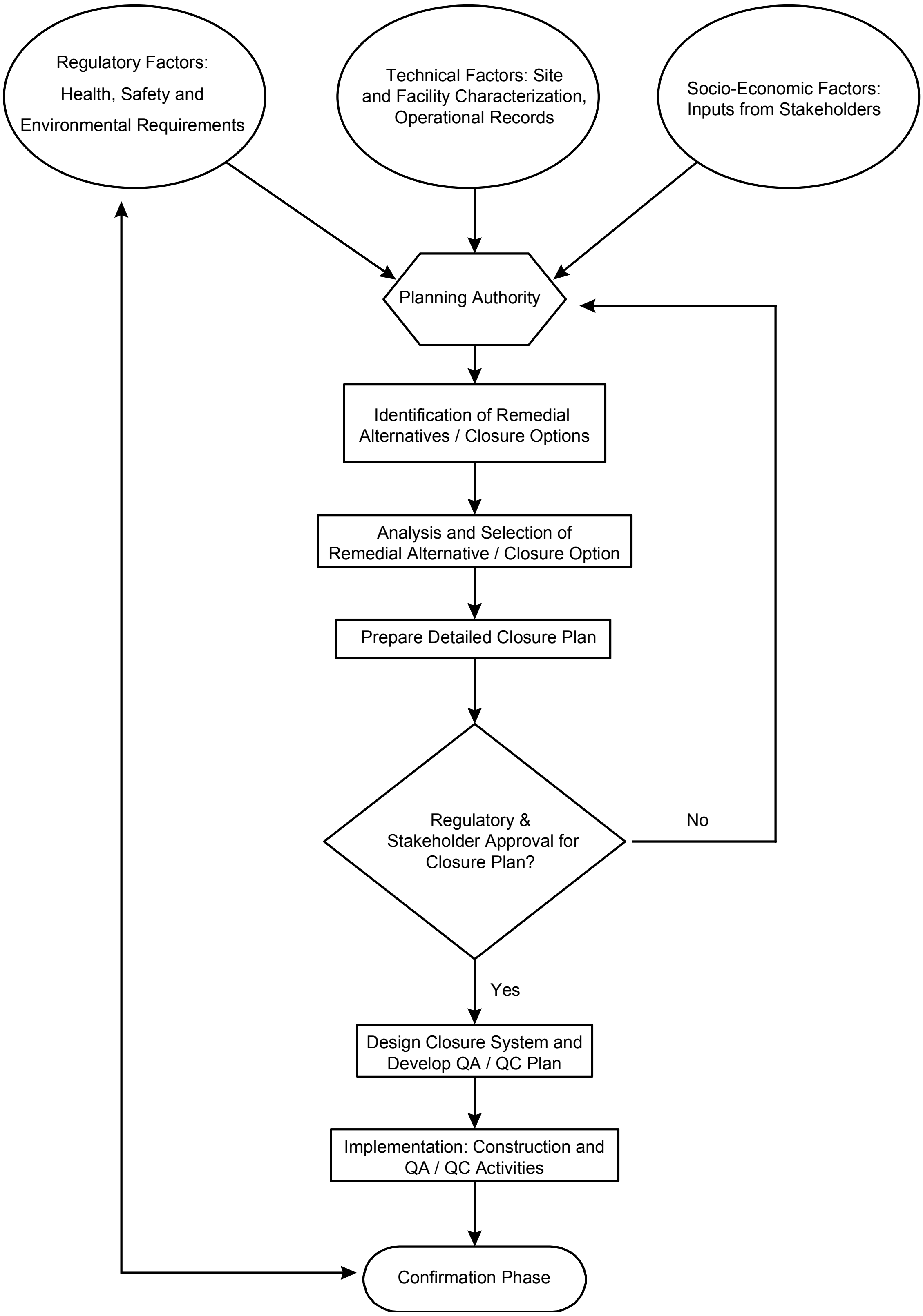

FIG. 1. Process for closure of near surface disposal facilities.

2. PLANNING FOR CLOSURE

2.1. CONCEPTS AND ROLE OF CLOSURE

Closure of a disposal facility that was managed from the outset as part of an integrated planning process would occur after its capacity has been exhausted and the facility is no longer operational. Figure 2 shows the lifecycle of a repository that includes planning for closure in the overall repository design (time frames are examples only). However, premature closure of a repository could be required either due to accidents (e.g., earthquakes, flooding, fires) or due to changes in public attitudes, demographic status, or the regulatory environment. If such a circumstance were to arise, corrective actions might be necessary. Repository closure is complete when the regulatory body, confirms that the closure activities have been performed in an acceptable manner, that the appropriate documentation is available and that provision has been made for post-closure controls.

In some cases, closure of portions of currently operational facilities occurs while the active operations continue on other parts of the facility. Partial or interim closure, particularly involving temporary or permanent vegetated caps and surface water management structures, can be beneficial in the sense that it would prevent or limit ingress of water to at least some parts of the facility. Partial closure may also be required due to regulatory changes or accident circumstances. Situations of partial closure are not considered here as they are expected to be part of operational procedures. In the case of a facility operating over a long period of time, closure of disposal units that have reached their capacity is a prudent action that can yield valuable monitoring and performance data when it comes time to cease operations and close the remaining disposal units (e.g., monitoring of subsidence or monitoring of leachate from closed units).

In general, disposal structures, including unlined earth trenches, are required to have closure systems that provide control on ingress of water or egress of gas. The closure systems are also required to protect the workers, performing institutional control measures such as monitoring and maintenance, and members of the public against hazards posed by the waste. The closure system is expected to function with minimal maintenance, without losing integrity, by promoting drainage to minimize erosion, infiltration, and accommodate settling and subsidence. The portion of the closure system under the cap will ideally have a permeability less than that of the bottom of the disposal unit to prevent ponding of water or what is known as the “bathtub effect”.

Institutional control may be required for an appropriate duration after closure of a disposal facility [5] to:

- prevent intrusion into the repository,
- prevent removal of, or interference with, the radioactive waste,
- confirm the satisfactory performance of the repository by monitoring,
- perform remedial actions, if necessary.

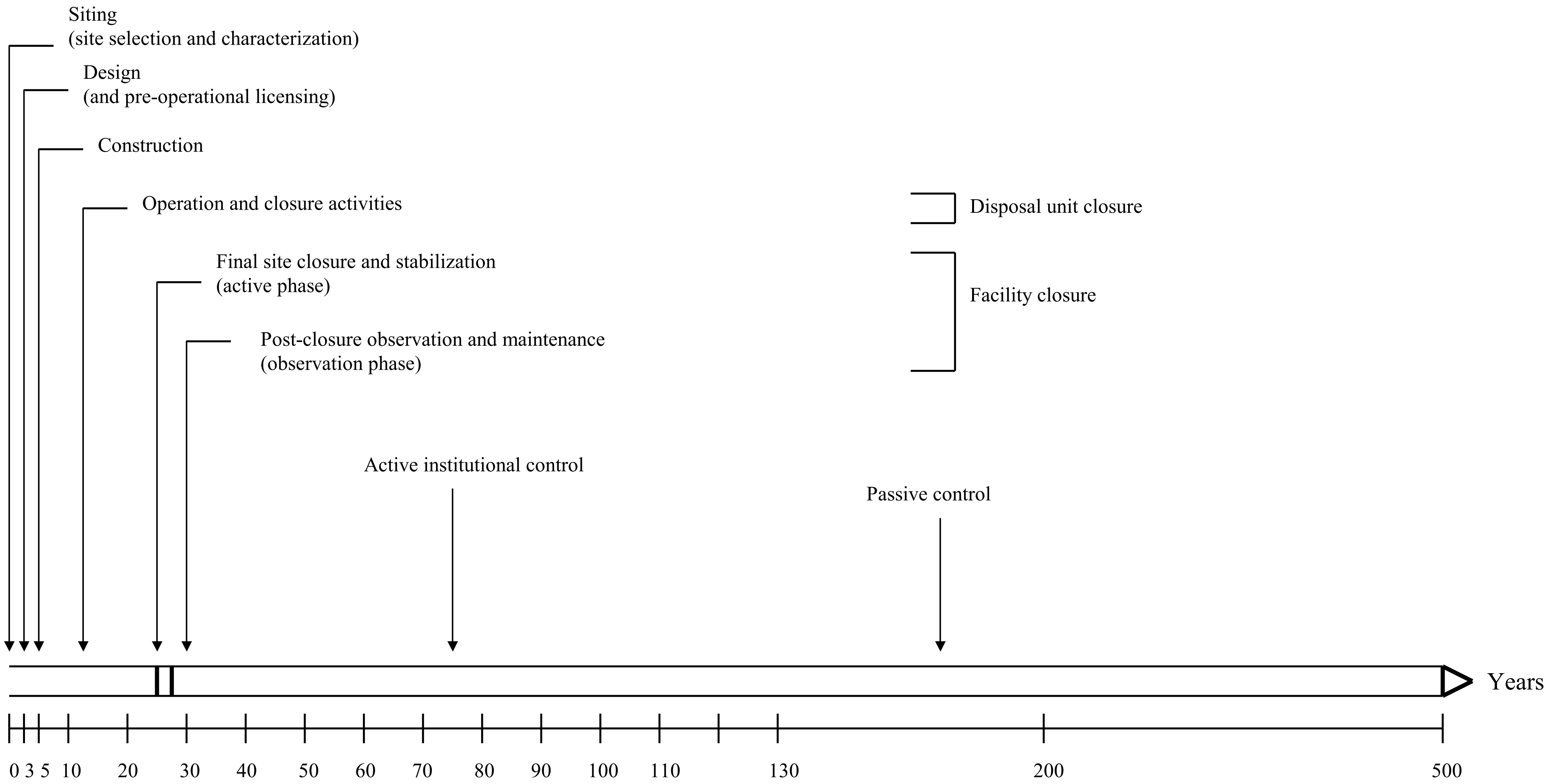

FIG. 2. Relationship of closure activities to repository lifetime (time frames are examples only).

A key consideration during the institutional control period is the post-closure monitoring to confirm the performance of the closure system. Post closure monitoring promotes confidence in the closure system and provides a defensible rationale for implementing corrective actions, if required.

Closure for a new disposal facility is usually considered during the initial design phase so that the individual elements of the facility are integrated to safely isolate waste [6]. Operational procedures and waste acceptance criteria are best developed with closure of the facility in mind. When the closure plan is integrated into the facility design and operational procedures, the level of effort and costs involved in closure are much reduced. Final closure, in this case, is then the logical culmination of design and operational activities intended to maximize repository integrity and performance.

Disposal facilities that were not sited, designed or operated in a manner that would meet current regulatory standards (such as legacy facilities) may require more extensive closure activities. For these repositories, an analysis of remedial alternatives may be required before any closure activity is undertaken. The outcome of the remedial alternatives analysis might range from taking no additional action to complete removal of the wastes. The focus of such efforts is typically on the design of a cap over the waste, however, stabilization measures such as *in situ* grouting or dynamic compaction may also be required. Repository closure, when it involves remedial measures, will generally require considerably more effort and expense than closure of a facility that was licensed and planned in an integrated fashion.

2.2. ANALYSIS OF REMEDIAL ALTERNATIVES

Some countries have LILW disposal facilities that were filled, and in some cases covered (e.g., by a simple cap of native soil), before systematic methods of safety analysis were developed. This problem is not unique to radioactive wastes - a similar situation exists for hazardous waste sites in many countries (e.g., the so-called Superfund sites in the United States). Many of the "legacy" disposal facilities may require remedial actions that are more extensive than simply the installation of a cover. Examples of the types of facilities that might require more extensive remedial action include unlined trenches and seepage pits.

A systematic analysis of remedial alternatives is usually conducted prior to taking any major remedial actions. The main steps in a remedial alternatives analysis are [7]:

– Problem definition - conduct a thorough investigation of the site to gather sufficient information to conduct an analysis of present and future safety (e.g., investigate groundwater flow system and estimate the contaminant inventory).

– Establish performance/remedial objectives that satisfy regulatory requirements and address public concerns.

– Develop and analyze remedial alternatives - identify a suite of remedial alternatives and apply a systematic methodology to assess the risks and benefits associated with each alternative. The suite of remedial alternatives could include options such as complete or partial retrieval of the wastes or *in situ* stabilization of wastes and installation of a cover system.

– Selection of a remedial alternative that satisfies regulatory requirements and public concerns.

An analysis of the no-action alternative (i.e., the baseline) identifies the need for remedial action and provides a baseline for comparative purposes. If the wastes are to remain in place then a closure plan would have to be developed for regulatory approval, and a closure system would have to be designed and implemented. If complete removal of the wastes were required, then there would be no need for closure system components such as a cover or cutoff walls or drainage systems. However, after removal of wastes, site monitoring might still be required for a period of time.

If a repository is designed and operated taking into account the complete life-cycle of the facility, the need for a remedial alternatives analysis is not necessary. Uncertainties associated with post-closure performance would be greatly reduced because the facility would have multiple barriers (e.g., waste form, backfill, concrete vaults, engineered cover) and would have operated from the outset with well-defined waste acceptance criteria.

2.3. CLOSURE PLAN

The first step in the process of repository closure, for both current and legacy facilities, is the requirement that the facility operator submit a detailed closure plan to regulatory authorities and obtain approval prior to its execution [3]. Preliminary closure plans may have been developed during the siting or pre-operational phase of repository development; the detailed closure plan provides an up-to-date and comprehensive description of repository closure. The detailed closure plan usually includes the following:

– Roles and responsibilities for organizations involved with closure and post-closure care of the facility,

– A detailed description of the closure method,

– An updated safety assessment for the facility,

– A monitoring and surveillance plan,

– A description of the record keeping and record preservation system,

– Long-term controls that will be implemented during the post-closure phase.

Closure plans for facilities have to reflect any "as built" modifications to the original facility or operational practices that would affect the results of safety assessments. The primary objective of the closure plan is to satisfy regulatory requirements and address public concerns to achieve safe isolation of the waste in a cost-effective manner.

The discussion that follows in Section 2.4 provides a description of the main types of information that would be needed to support a detailed closure plan as well as a remedial alternatives analysis. Section 2.5 provides a brief overview of important performance criteria for closure systems - criteria that, in many cases, would become essential performance requirements in detailed closure plans.

2.4. FACTORS FOR CONSIDERATION IN THE CLOSURE PLAN

As illustrated in Figure 1, there are three major factors to be considered in evaluating closure alternatives: (a) scientific and technical input; (b) regulatory requirements; and (c) socio-economic considerations. These factors are initially considered in concert to define the objectives and goals in closing the facility, identify candidate closure alternatives, and specify the technical, regulatory and economic constraints associated with a particular management alternative. The decision to use a particular closure option is based on an analysis and integration of all relevant information.

2.4.1. Regulatory requirements

Repository licensing is often carried out in phases, with separate licences for contruction, operation and closure. The requirements for closure will depend on the national regulatory body, however, the following would generally be included: reasons for closure, a detailed closure plan, a process for public consultation, the final performance assessment and a quality assurance (QA) programme. The application for a license for closure is required to demonstrate the level of safety for radiation protection of workers, the public, and protection of the environment.

The actions associated with repository closure are developed to comply with environmental regulations prevailing in the Member States. The physical state of the disposal facility, prior to closure, may differ, depending on national regulations and operating conditions. Regardless of these differences, a common requirement is that the operator, the national authorities, and the public have a sufficient level of confidence that the repository system will satisfactorily perform its intended safety functions.

Depending upon the requirements of the specific Member State, an environmental impact assessment may be performed that takes into account the impact of repository closure operations on such factors as noise levels, dust generation, increases in traffic, impact on local flora and fauna, and human receptors. If closure considerations have been integrated into the facility design, operational procedures, and waste acceptance criteria, the initial environmental impact statement may already address the impact of closure operations.

2.4.2. Quality assurance

As part of the detailed closure plan, a QA programme for closure/post-closure of the repository is developed, implemented and maintained to demonstrate compliance with regulatory requirements [8,9]. The purpose of the QA programme is to ensure that the disposal facility is closed in accordance with the closure plan, and design and construction specifications. Another important aspect of QA is to ensure that a permanent record of closure activities is maintained. The record would include documents such as, regulatory correspondence, closure plan, test results, construction drawings, design reviews, procedures, logbooks, as well as detailed information on the contents of the repository, especially waste inventory and characteristics. The regulatory body will review the QA programme for the closure activities and may identify QA measures that have to be carried out independently of the operator [8].

Pre-Construction: Before construction of closure systems can begin, the operator has to develop a QA programme containing written plans and procedures to manage the design and construction phases of closure. QA documents are defined prior to initiating any design or construction activities. These quality documents describe the manner by which the disposal facility operator will maintain assurance of quality during the design phase. Topics covered in the QA plan include organization, design control, reviews and audits, technical reviews, materials acquisition, and material testing.

During Construction: During construction of closure systems, the principal activities of the QA programme centre mainly on maintaining a record of the quality control activities. These quality control activities are the actual procedures used to control construction processes used for installing closure system components [see Section 4.3.6]. Controlling modifications and changes to the closure system design are also a significant aspect of QA during the construction phase.

Post-Construction: Post-construction QA activities focus primarily on the maintenance of records. Examples of the types of records to be maintained include maps, test results, construction logbooks, unusual events, and design, as well as information on waste inventory and characteristics. The main objective is to create a complete record of the disposal facility's contents, closure design and construction process so that it will be available and understandable to future generations. The records that describe disposal facility closure are, therefore, an essential part of the overall disposal facility record, and maintained in secure storage locations to assure longevity and availability of the information. The QA record of facility closure is of importance to future generations, especially if repairs or modifications to the facility are needed in the future.

2.4.3. Waste inventory and characteristics

In facilities that were shut down many years ago, the waste forms, packaging and radionuclide inventories are not usually well known. Consequently, historical records of facility construction and waste emplacements, knowledge of waste generation and monitoring data are needed to identify potential contaminant migration problems and to help in designing the closure procedures and specific techniques.

In general, only waste that will decay to acceptable activity levels during the period of time for which institutional controls are expected to continue are acceptable for disposal in near surface disposal facilities [3]. Radionuclides with long half-lives, in relation to the period of institutional controls and for which no significant radioactive decay will occur, are expected not to exceed the acceptable levels at the time of disposal [4].

The physical form of the waste is an integral part of the closure design, affecting the potential for subsidence, biodegradation, and susceptibility to leaching. Establishing specifications for physical characteristics of the waste and the concentrations of radionuclides is an important part of closure planning for new disposal facilities. Some examples of waste that might be received for disposal into near surface disposal facilities are given in IAEA publications [4,10].

Packages need to have specifications for the maximum amount of void space inside the package to limit the potential for localized and general subsidence. Waste emplacement, backfilling, and interim cover placement is best performed in accordance with established procedures and a QA programme. Waste packaging, package placement, and backfilling procedures during the operational phase of the facility greatly reduces the dependency of the disposal facility on the cap alone.

If the waste placed in the facility is known to have unfavorable physical, chemical or biological characteristics, such as high leachability, high dispersability or high gas generation, it may then be necessary to consider corrective or mitigative action as part of the closure plan. Corrective actions to control contaminant migration from the disposal units may include leachate treatment systems, emplacement of barriers above and surrounding the disposal units to mitigate water ingress, or installation of venting systems to allow gases to escape.

2.4.4. Site characteristics

Site location and associated characteristics are key factors in the selection of engineered features, operational procedures, waste acceptance criteria, and closure design for a disposal facility. For closure design, site characteristics directly impact the materials selected for erosion control, hydraulic barriers, and re-vegetation. The major issues associated with the siting of near surface disposal facilities have been described elsewhere [11]. The following discussion introduces several key aspects of site characteristics that are important considerations in planning for repository closure.

Topography: Avoiding areas that have large watersheds above a proposed facility is important to minimizing the threat of surface water management problems. However, for those existing facilities located in areas with hilly terrain, canyons, or where disposal is below ground, topography and its effects on surface water is an important issue. In these environments, a considerable amount of surface water run-on may occur, and the designer is required to manage or prevent run-on from entering the cap and those areas immediately adjacent to the disposal units. The designer can assess potential run-on problems by performing an analysis of surface water flows. Perimeter or central drainage systems can be installed to divert run-on away from disposal units. Care is taken to ensure that measures taken to promote drainage do not enhance erosion to unacceptable levels. Maintaining subcritical flow velocities and lining drainage channels are means to minimize erosion.

Precipitation: Data on the intensity, duration, and frequency of storms is needed to calculate the volume of surface water run-on or run-off. The calculated rate of infiltration into the soil and percolation through the waste disposal unit will directly impact the design of the closure system, including the cover and drainage layer/s. For example, calculated infiltration and percolation rates based individual precipitation events such as the probable maximum precipitation may result in more rigorous closure system requirements than, for example, a design based on average annual precipitation. If there is flooding potential, the flood characteristics (e.g. stagnant backwater or scour potential due to flow) need to be evaluated, and measures designed to prevent damage to or failure of closure systems. Likewise, special consideration is given in evaluating the effect of snow accumulation on the site and the effect of melting snow on soil water recharge.

When available, site-specific precipitation data is the best source for design calculations, although climate prediction computer codes could be used in the absence of site specific precipitation data. Precipitation data, particularly the annual distribution of rainfall and snow, is critical to the selection of the drainage systems, surface water diversion structures, cover materials and design, and types of vegetation to be established on the cap and surrounding areas. Consideration of native species for re-vegetating the disposal facility is important since these species have adapted to local conditions, are often fire and drought resistant, require minimum irrigation, and require little or no maintenance. Use of such vegetation species will enhance cover performance by intercepting and transpiring infiltrating moisture.

Other climatological data: In climates that experience freezing temperatures or drought, the upper surface layers of a disposal unit closure system and cap may be damaged by frost heaving leading to buckling or sliding of layers after thawing or by cracking during extended periods of drought. As a general rule, cover designs that incorporate geomembranes, concrete caps, or low permeability soil layers, are most susceptible to damage due to severe weather and need to be placed below the depth of freezing or severe drying. Freezing also increases the amount of surface water run-off expected during winter months, as percolation through frozen ground is limited.

Hydrogeology and soils: In situ soil and hydrogeological characteristics are important because they influence lateral and vertical movement of ground water and soil moisture, bearing capacity, hydraulic conductivity, moisture storage capacity, and liquefaction potential of the various layers of the cover and subsoil. An assessment of the properties of the in-situ soils is required for design calculations to evaluate processes such as drainage system performance and water balance calculations.

2.4.5. Design

Closure procedures and techniques are usually site- and facility-specific. Many different designs of near surface disposal facilities were developed in the past. Typically, they consist of emplacement of waste in structures that were constructed (a) beneath the ground surface, e.g. trenches, pits and wells, and or (b) above the ground surface, e.g. earth-covered mounds or engineered structures. More details on past disposal practices can be found in other publications [1,2,12,13].

Many disposal facilities, especially those designed after the late 1970's, gave at least some consideration to closure activities early in the life of the facility. For example, consideration was often given to:

- establishing waste form and concentration acceptance criteria,
- limiting void space in packages,
- waste emplacement and interim cover placement procedures,
- load combinations and strength considerations for foundations and structures,
- buffer zones around the facilities, and
- technical means for sealing or removing operational systems after they have served their intended function.

Repositories are usually designed to include space needed for the cap and surface drainage systems as well as preparatory or material handling areas needed for closure implementation. Good design practice for closure will facilitate instrumentation emplacement and sealing.

2.4.6. Operational experience

The operational experience at the facility is an important source of information to be considered for closure planning. Site-specific, meteorological data gathered over many years of operation provide valuable input for cover design calculations. The records and logs of disposal activities can provide information related to the types of waste received, waste emplacements, and any operational difficulties, such as unexpected subsidence, erosion or leachate production. If operational records and monitoring records indicate that there is very little subsidence, little or no release of radioactivity, and good stability of the facility and site under a wide range of meteorological events, perhaps some consideration can be given to simplifying the approach to closure.

2.4.7. Public acceptance

Public consultation is a critical component of the decision making process for closure. Public opinion and attitudes usually have a major influence on siting, operation, types of waste accepted, closure and post-closure control of disposal facilities. Repository closure usually includes a public consultation phase. Closure-related issues that are likely to be of public concern include:

- Health, safety and environmental impact assessments,
- Traffic management, and noise and dust suppression measures,
- Contamination control measures,
- Any disruptions or increased demands on local services,
- Control of access to the site,
- Impact on local employment,
- Visual appearance of the site after closure,
- After-care of the facility (post-closure monitoring, surveillance and land use restrictions).

Safety and environmental impact documents and information concerning construction activities need to be provided to the public on a periodic basis in a form that is reasonably concise and that can be understood by a non-technical audience. A wide spectrum of interests may be represented by the public; final decisions on closure plans for a repository are expected to represent a satisfactory balance between the interests of all parties.

2.4.8. Human and financial resources

Member States implementing closure and post-closure activities are required to provide qualified staff and financial provisions to implement closure activities, as well as adequate resources to enable the appropriate institutional controls and monitoring arrangements for the period deemed necessary to confirm closure system performance. Staff training in the areas that are relevant to implementing the closure programme is an important consideration. The training selected for the staff will be similar to that used during the operational period, but will be augmented with topics specific to closure activities such as industrial safety related to earth-moving activities, precautions when handling geomembranes, and dismantling and decontamination of support buildings [9,14].

The technical basis for defining the closure system can be derived from the health and environmental risk assessments. Ideally, these assessments are performed during the design phase of the facility or at least many years in advance of the expected closure date because significant savings can be realized by integrating closure objectives into the disposal facility waste acceptance criteria and operational procedures.

2.4.9. Closure experience: hazardous and municipal waste management

Closure technologies for radioactive waste disposal facilities and hazardous and municipal waste disposal facilities have much in common. The number of municipal and hazardous waste facilities is much larger than the number of LILW disposal facilities, and because they are often thought to present less hazard many more of these facilities have gone through the closure process. The accumulated experience associated with closure of hazardous [15] and municipal [16] waste facilites is correspondingly larger. A great deal of the development work for covers, liners, cutoff walls, geosynthetics and leachate collection systems has been carried out for either hazardous or municipal waste facilities.

There are significant differences between radioactive and hazardous/municipal waste disposal facilities that have an influence on closure plans and some aspects of closure technology. These include:

The duration of the institutional control (IC) period. For a municipal waste facility the institutional control period is typically about 30 years, and some municipal waste sites have already been re-developed for other uses. The IC period for hazardous waste facilities (i.e., secure landfills) is essentially indefinite, until it can be demonstrated that the leachate is no longer toxic. Radioactive waste repositories generally have an IC period that is long (100 to 300 years), but well defined by the half-life of the relatively short-lived fission product inventory in the facility.

The stability of the wastes. Subsidence is a particular concern for municipal waste facilities due to the very heterogeneous nature of the waste and its biodegradability. Subsidence is easier to manage with radioactive waste because the wastes usually do not contain an appreciable fraction of biodegradables, such as a putresibles, and radioactive wastes are usually stabililized prior to disposal (e.g., by solidification in matrices such as cement).

Contaminant toxicity. Unlike municipal waste, the external radiation field associated with radioactive waste, especially the hazard associated with inventories of disused sealed sources, requires special handling and protection measures that are unique to radioactive waste.

Although there are some basic differences between radioactive and hazardous/municipal waste disposal facilities, from the point of view of closure technology, there is also some commonality between LILW disposal facilities and hazardous and municipal waste facilites. The extensive experience with closure of hazardous and municipal waste facilities is reflected in:

- The large variety of cover designs that have been field-tested.
- The development of novel liner and cover materials (e.g., geosynthetic drainage materials and composite membranes).

- The development of seam types and seaming procedures for geosynthetics.

- The development of construction QA and QC procedures, as well as manufacturing QA and QC.

- The development of a large number of standards, specifications and test methods for design and installation of closure systems.

The publications on closure of hazardous and municipal waste disposal systems can serve as a valuable resource for the design and planning of closure systems for LILW disposal facilities. Some of these reports are given in [9,17-19].

2.5. PERFORMANCE REQUIREMENTS AND CRITERIA

2.5.1. General requirements

Closure systems are designed to satisfy a number of requirements to ensure the long-term safety of the repository. The design requirements for a closure system are derived from regulatory input, public consulation, economic considerations and technical analyses. There are a number of general requirements that all closure systems are expected to meet to ensure the long-term integrity of the facility. These include:

- *Impermeability* — the amount of rain water penetrating the cap and/or other structures and coming into contact with the waste is expected to be low to limit radionuclide leaching and subsequent migration;
- *Integrity* — the waste, cap, and surrounding structures are designed to retain the required material integrity under all environmental conditions, including climatic extremes, subsidence, natural events such as fire and earthquakes, chemical and microbial degradation of soil and barrier materials, and mechanical load;
- *Resistance to degradation* — the waste form, cap, and surrounding structures are designed to prevent degradation due to external forces such as erosion, freeze-thaw cycles, and biological intrusion. The disposal cap is designed to be sufficiently thick and made of appropriate materials to protect the disposal units from such external forces;
- *Reparability* — while performance requirements are stringent, the probability of failure of one or more components of the system can not be ruled out, especially over long time frames. Design features that facilitate maintenance or features that limit the need for maintenance are preferred. As a general rule, simple closure designs tend to facilitate corrective actions. In addition, post-closure monitoring techniques can be designed to quickly locate areas where a cover may have failed or where unexpected subsidence has occured, thereby allowing corrective actions to be taken while the problem is relatively small.

These general requirements would apply to closure of both shut down and planned disposal facilities [14, 20–22].

2.5.2. Guidance from performance assessment

The long-term safety of repositories is generally evaluated using the performance assessment (PA) methodology. PA can identify a general set of performance criteria for the closure system (e.g., limits for infiltration rates, service lifetime required of cover, requirements to mitigate intrusion risk). Closure systems are subsystems of the overall waste disposal system, and thus are evaluated in concert with the overall PA.

Potential radiological impacts following closure of the facility may arise from processes, such as degradation of barriers or from other events that may affect waste isolation [23, 24]. The general framework for conducting a PA for a repository consists of a number of interrelated and iterative elements:

- identification of closure features, events and processes, or scenarios, that could influence release and transport rates from the waste to the geosphere and biosphere to humans (see Section 3.1.2);
- definition of those closure systems and scenarios of critical importance;
- consideration of the disposal facility's projected and actual source term, including the physical form and chemical composition of the waste;
- consideration of the disposal facility's operational plan or history which forms part of the basis for the closure system and the associated PA,
- evaluation of the effects of various components of the closure system and scenarios against the base case PA for the disposal facility;
- consideration of the uncertainties in the results and identification of the parameters and assumptions that are of most importance ("uncertainty and sensitivity analysis"); and
- comparison of results with the appropriate performance standards and regulatory criteria (see Section 2.3).

The emphasis given to each of the closure system elements in the PA may vary according to the purpose of the assessment and the current level of understanding of the disposal system. In general, a PA requires values for a broad range of input parameters that are specific to each facility and based on the facility design, local climate, geological setting, operational practices, and dose or risk standards. Generic assessments are not based on data representative of any particular repository but are useful in evaluating various closure alternatives especially when they are used in the early design phase of a disposal facility. However, the amount of information available from any generic PA is limited because the risks associated with any particular repository are intimately linked with site-specific factors. As part of the PA, sensitivity analysis is usually used to determine which closure system elements are most important for safety.

The design of some disposal facilities built in the past may not have included any PA evaluation of a closure system. In these cases, closure systems are usually compared with a base case PA to determine the potential of the closure system to mitigate release of radioactivity to the biosphere.

2.5.3. Detailed design criteria

PA can identify the broad performance requirements for repository closure systems, however, a more detailed level of assessment is needed to arrive at a detailed design for the type of closure system that will meet these requirements. Criteria specific to closure system design can be performance driven (derived from site and facility-specific models) or prescriptive (i.e., regulatory criteria that apply to an entire class of facility). The detailed criteria required for design and evaluation of a muti-layer cover incorporating resistive and capillary barriers, or the criteria required for design and evaluation of a surface water drainage system are seldom included in PA models. Examples of performance criteria needed for detailed design calculations are:

- infiltration rate to the cap,
- freeze-thaw depth,
- run-off and erosion,
- compactness and strength of cap layers,
- compactness and strength of waste layers,

Detailed design criteria are derived from a combination of factors, such as field experience, engineering judgement, hand calculations and computer models, especifically designed for cover system evaluation. Models and calculations for detailed closure system design are described briefly in Section 3.4.3.5.

3. ANALYSIS AND SYSTEM SELECTION

3.1. CLOSURE SYSTEM FEATURES

There are major engineering components that may be used for closure of disposal facilities:

- a cap with or without a low permeability (resistive) layer,
- cut-off walls designed to minimize lateral migration of either leachate out or groundwater into a repository,
- drainage features to conduct surface and subsurface water and potential leachate away from a repository,
- markers to indicate the presence of a closed repository to future generations.

A disposal facility may incorporate one or more of these features. By far, the most common feature will be a closure cap designed to provide intruder protection, reduce infiltration, and to minimize biointrusion and surface erosion. This section provides an overview of current knowledge on the design, materials selection, construction, maintenance, and quality control of components of closure systems.

The structural components of a closure system are employed to mitigate one or a number of the potential routes by which radionuclides can escape from a repository. These components can be classified into primary and secondary components. Primary components have a direct role in the mitigation of an exposure route, e.g. water ingress and egress. Secondary components are there to protect the primary components from degradation and damage. Both primary and secondary components can be combined in various ways into the four major types of closure system components, namely caps, cut-off walls, drains and markers. These components are outlined below with emphasis on the primary and secondary components of which they are composed.

3.1.1. Covers

The installation of a cap is often the minimum requirement for a disposal facility. A cap may be installed for a number of reasons, principally to prevent infiltration of water, human intrusion, exposure of the waste by erosion, and escape of radioactive gas, e.g. radon, tritium. In many cases, caps are designed with more than one, if not all, of these functions in mind. This multi-functionality has played a part in the development of multi-layer caps where each layer performs different functions, but together they contribute to the overall performance objective of the cap. In the case of preventing water ingress, there are four basic types of barrier [2, 21, 22] concepts that may be used individually or in combination. These concepts are described below:

- The *resistive barrier* (Figure 3) is based on low-permeability material such as compacted clay or geosynthetic clay liner that is designed to impede flow of water into the repository.

– The *conductive barrier* (Figure 4) employs the capillary barrier phenomenon to divert water away from the waste. The barrier consists of a highly permeable material, such as course gravel, underlying a fine-grained material, conductive layer. Because of the differences in saturated hydraulic conductivity between the two layers (ideally about a factor of 1000), a capillary break is formed at the interface of the two layers. Water is diverted laterally in the finer textured soil above the layer interface when it is at a negative capillary tension. Under these conditions, the barrier prevents liquid from crossing the capillary break. The barrier will continue to operate as long as the overlying low-permeability zone does not become saturated. Upon saturation, the efficiency of this barrier is reduced.

– The *infiltration control barrier* (Figure 5) uses enhanced run-off as a means of controlling the amount of infiltration and subsequent water percolation to the waste. The need for infiltration control techniques stems from the fact that soil moisture removal by vegetation has an upper limit. Thus, in climates where annual precipitation exceeds the upper limit for evapotranspiration, the probability of water percolating to the waste increases. By limiting infiltration through enhanced run-off, facilitated by using an impermeable cover with drainage channels, to amounts that can be removed by the vegetation, the probability of water percolating to the waste is minimized.

– The *vegetated soil cover* (Figure 6) plays an important role in the management of water through protection of the soil surface against erosion and, more importantly, through removal of soil moisture by plant transpiration and evaporation from the bare soil. If the design is based on an optimum combination of soil type, soil depth, surface slope and vegetation species, then storage and removal of soil moisture by plant transpiration and evaporation from the soil surface is maximized [22]. All near surface disposal facilities that use a final soil cover, as a part of the closure system, can benefit from the use of a well designed vegetation cover. In humid environments, evapotranspiration may remove up to 80% of the water that infiltrates into the cover soil. In arid and semi-arid environments, vegetation cover may remove 100% of the moisture that infiltrates into cap soils. Thus, vegetation cover is an inexpensive, but highly effective means of managing soil moisture in a repository closure cap, particularly if care is taken in selecting the plant species and the vegetation procedure.

– The multi-layer cover (Figure 7): Various combinations of all these barriers are possible and desirable if local conditions warrant it. Several multi-layer barrier systems have been proposed [25-35]; one of these is outlined in Figure 7 to illustrate possible barrier combinations. This multi-layered design consists of a rock or vegetation top layer to stabilize the underlying drainage layer, which diverts downward movement of soil moisture. This layer, in combination with the overlying soil layer, can also function as a capillary barrier. The main infiltration barrier or resistive layer is composed of low-permeability clay or soil. Any water that penetrates the low-permeability clay/soil layer is scavenged by the underlying conductive layer, composed of diatomaceous earth, which diverts the flow laterally around the waste. The conductive layer is underlain by a gravel layer, both of which form another capillary break. The final layer is the concrete in which the waste packages are immobilized. The design shown is of an above ground system and therefore the geometry of the mound is important to ensure maximum run-

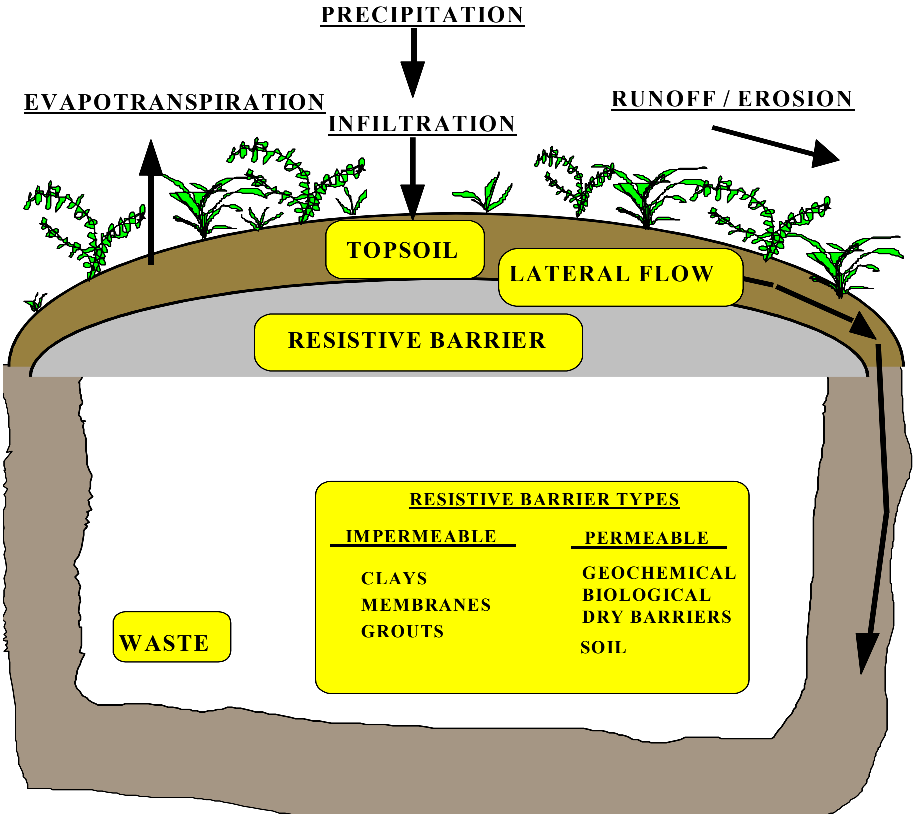

FIG. 3. Resistive barrier.

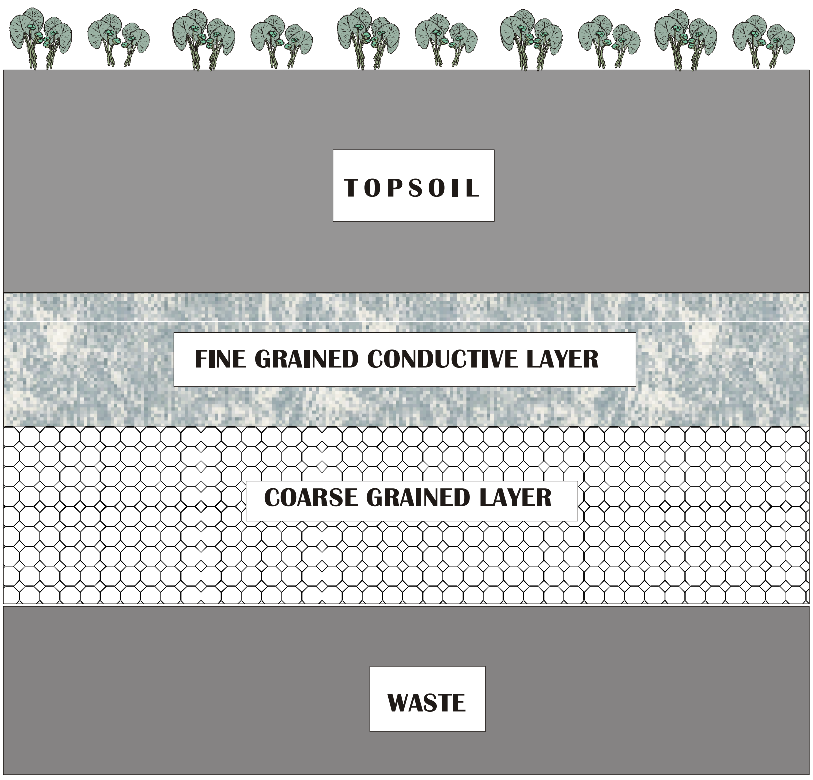

FIG. 4. Conductive barrier.

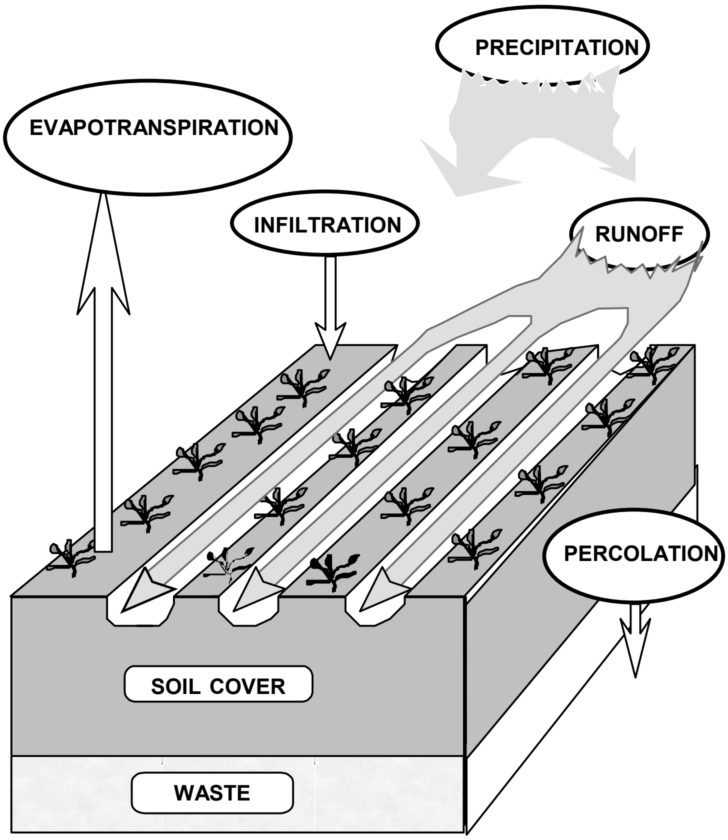

FIG. 5. Infiltration control barrier.

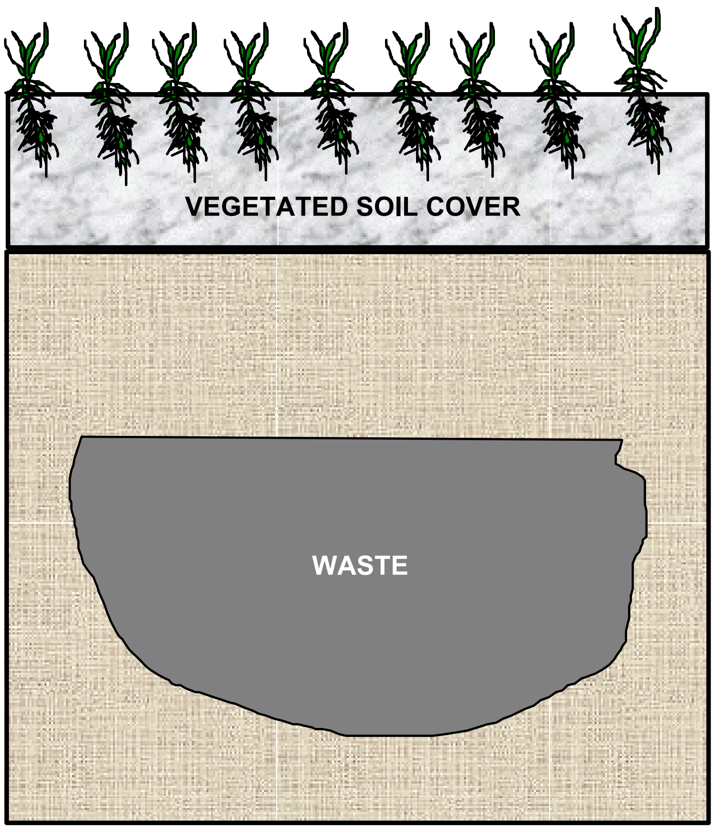

FIG. 6. Vegetated soil cover.

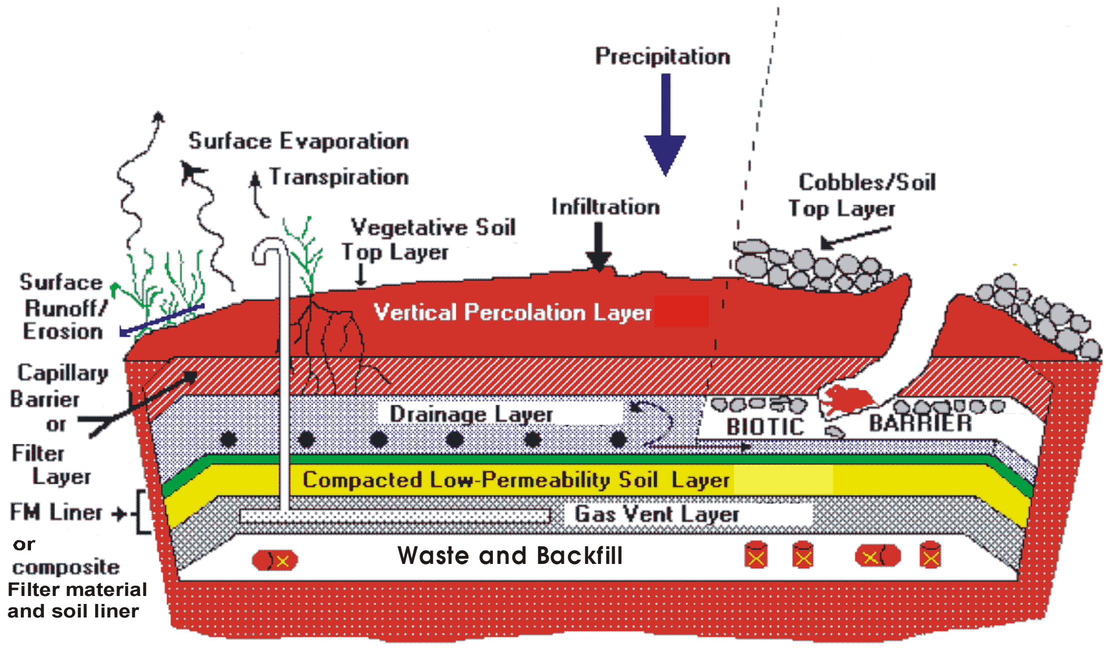

FIG. 7. Multi-layer cover.

off and minimum erosion. Even in below ground disposal systems, designing caps with a geometry which promotes run-off, while controlling erosion to acceptable levels, will help prevent standing water and reduce the potential for infiltration.

In addition to the barriers outlined above, potential cap designs may also include intrusion barriers to prevent human or animal intrusion. These may be layers that alert the human intruder to potential hazards and may consist of concrete or cobbles [30-32]. Cobble layers have also been shown to be effective in preventing intrusion of small mammals and plant roots to the waste [30]. Under certain circumstances, caps may also require provisions for the venting of gas generated during waste degradation. Gases such as methane and hydrogen can be generated during the microbial degradation of organic waste and/or the corrosion of metallic waste and containers composed of iron/steel and aluminium. If these gases are not allowed to escape, a build up of pressure will occur which may damage the repository and allow lateral migration of potentially flammable and explosive gases to areas where they may pose a danger.

The requirements for the cap are performance-based; therefore, the elements incorporated into the design may vary depending on the type of materials available, the environment in which it is placed, and the type of waste to be interred. The cap design drawings usually include the following:

- a plan view of the LILW disposal facility,
- cross-sections at several locations,

- details where cap components key into the liner system (if required),
- details for cap connections between adjacent units,
- details of penetrations such as leachate removal manholes or gas vents (if required).

Drawings have to clearly show the cap configurations, the dimensions (thickness, slope) of each element, and the finished elevations of the tops of the soil layers at critical points. These drawings need to reflect the same dimensions and slopes used in the design calculations, especially those involving runoff controls, percolation estimates, and drainage layer performance.

3.1.2. Cut-off walls

Cutoff walls are generally employed to prevent lateral ingress of groundwater into a disposal facility or the egress of leachate [21]. These walls may be placed during construction of the facility or constructed at a later date to upgrade an existing facility. They are generally constructed of either reinforced concrete which may or may not include additives to reduce its permeability or mixtures of soil and bentonite or cement and bentonite may also be used. Geomembranes may also be used either on their own or as a component of a slurry wall.

There are a number of methods of placing a cutoff wall around a disposal facility. One method is slurry trenching where walls are constructed by the excavation of a trench down to an impermeable layer. The trench is prevented from collapsing by a combination of the shear strength of the soil and flooding with a fluid such as a dilute bentonite mix or even water. The wall can be constructed by displacement of the fluid by injecting concrete into the bottom of the trench or by using self hardening slurries of hydraulic cement and bentonite or bentonite and soil. It is possible to reinforce these walls in a similar manner to conventional reinforced concrete or to add various geomembranes to enhance performance. If conditions permit, grout and bentonite based cutoff walls can also be constructed by the injection of the materials into the ground through a series of bore holes around the repository.

Cut-off walls, as with caps, will be susceptible to cracking which will significantly reduce their performance as barriers to water flow and radionuclide migration. Cracking may be caused by desiccation, differential settlement in the surrounding geology, stresses caused by settlement in the waste and through internal stresses caused by the deterioration of the concrete and steel reinforcements. Other processes also reduce the performance of cement and concrete-based systems, including sulphate and chloride attack. The short term benefits of cut-off walls are an important consideration as opposed to the large uncertainties in their long term performance.

3.1.3. Drainage systems

There are basically three approaches for drainage associated with the closure system of a disposal facility. The first of these is drainage management in the watershed upgradient from the disposal facility. The second is associated with the closure system and is designed to remove water away from the disposal units, using sloped caps and drainage channels. This drainage is an integral part of the capping system and has already been discussed in the sections dealing with caps and resistive layers. The third type of drainage is within the disposal facility and is designed to conduct leachate away in a manner that results in the most acceptable risks. It is this type of drainage, which is discussed in this section.

No barrier can be expected to be completely effective in preventing water ingress into a repository over long periods of time. Consequently, it is important that any water which does enter a disposal facility is allowed to escape. Internal drainage systems, designed to intercept any incoming water and conduct it away from the waste, are important considerations for disposal facility closure. Internal drainage generated by capillary or hydraulic barriers that create lateral flow will probably be the major source of drainage fluids, assuming that these barriers function properly over long periods of time. In most cases, the drainage system is most effectively installed prior to the completion of the disposal of waste. It is also important to take into account anticipated changes to the site hydrogeology when designing drainage systems. This is to ensure that future changes in the groundwater levels do not result in backflow through the drains resulting in water ingress into the repository.

Although ceramic, PVC, and other materials used for drainage pipes may have long lifetime performance, their poor structural strength means that they will be susceptible to damage due to differential settlement. Additionally, intermittent flows though pipes can cause clogging due to sludge build-up or mineralization. In view of this, highly permeable granular drainage systems, such as gravel, are among the preferred drainage construction materials. The use of natural materials means that they are less susceptible to degradation or damage due to subsidence and differential settlement, however, they are still susceptible to clogging.

3.1.4. Markers

Specific recommendations for permanently marking a near surface disposal facility are at best tentative given the relatively short history of LILW disposal [39]. Repository markers can be defined as on- or off-site structures which signify the presence and characteristics of a disposal facility. The aim of site markers is to protect future societies from the risks associated with inadvertent intrusion into the disposal facilities. Markers need to be designed to protect both low- and high-technology societies from these risks and are only relevant if they are likely to survive and be recognizable over long periods of time. The following discussion offers some potential approaches to marking a LILW repository, but other approaches, including electronic marking may be feasible in the future. Other candidate marking systems may be developed as technology and information systems improve.

Some possible passive marker systems might include warning markers which signify that dangerous human artifacts are present; detailed markers which give information on the nature and magnitude of the hazard. The long term survival of markers is crucial to their effectiveness and one approach to evaluating their long term integrity is to consider the survival of archeological structures.

3.2. MATERIALS

A wide variety of materials have been employed as barrier material in the construction of disposal facilities. These materials can be used either individually or in combination to provide the overall system with the required properties.

Clay has been extensively used as a barrier material due to its low saturated hydraulic conductivity, which ranges from 10^{-9} to 10^{-6} cm/s [21, 22, 25–27, 29, 30], giving average rates of infiltration in the region of centimeters or less per year. Due to its wide occurrence in nature, there is a possibility that clay deposits may be found on or adjacent to any particular repository or closure system under construction. If this is not the case, commercially available materials such as bentonites may be employed. Effective hydraulic conductivities for compacted bentonite range from 6.5×10^{-9} cm/s to 1.1×10^{-5} cm/s [25-30]. Bentonite may also be blended with local materials to produce a more economical alternative to the pure product and still retain the desired hydraulic properties.

The clay minerals have significant sorption properties for a broad range of radionuclides and, as such, they may act as both a physical and chemical barrier to radionuclide release from disposal facilities. Problems which may occur when clay is used as a barrier include erosion, dessication cracking due to diffusion of moisture from the clay into the surrounding soil, and plant root intrusion leading to moisture removal by evapotranspiration, as well as the creation of macropores. Chemical degradation due to waste liquors and effects due to freeze-thaw cycles are other processes that may lead to degradation of the clay barrier.

Concrete and cement are often used in engineered repository systems. They are generally applied to the construction of pads, footings, drains, cut-off walls, linings and as grouts and backfills. Concrete is widely used as a construction material and is recommended as an effective barrier to improve structural stability, reduce water infiltration, erosion and infiltration. Concrete emplaced in situ in a repository will generally be a more effective barrier than pre-cast concrete since no seals are required. The correct mixing and pouring techniques are essential for the successful utilization of concrete, if this is not done, cracking may occur which dramatically reduces its effectiveness as a barrier.

Cement-based grouts are routinely used in disposal facilities for the backfilling of voids within and between waste containers. The flow properties of these materials are controlled through the use of additives. Additives can be used to influence a wide range of cement/grout properties in addition to its flow properties. They can be used to either reduce or increase permeability, increase sorption, or reduce water content [35]. Cements and concrete based engineered barriers do not only act as physical barriers. Their presence in a disposal facility may dominate the chemistry of any infiltration and leachate, imparting an alkaline environment, which generally reduces the mobility of some radionuclides, especially the actinides and ^{14}C.

Asphalt containing materials e.g. asphalt containing concrete, hydraulic asphalt concrete, soil asphalt and hot liquid asphalt have been used as infiltration barriers due to their low permeability, ranging from 10^{-8} to 10^{-9} cm/s [2]. These materials can form highly durable barriers, but if incorrectly applied, they may crack in cold weather and degrade when exposed to the elements [2]. They are also subject to shear stresses in the repository.

Synthetic materials are used as infiltration barriers more commonly in municipal waste disposal facilities than in radioactive waste repositories. Materials such as polyethylene, polyvinylchloride, polyesters, epoxy resins, butyl rubber have extremely low permeabilities and can be welded or cemented to make a continuous cap [21]. Woven synthetic materials (geogrids) can also be combined with clay layers to improve their resistance to cracking. The combination of clays and synthetic layers allows thinner resistive layers to be used. Unlike concrete and bentonite, conventional synthetic materials have not been in common use for more than two decades. The basic problem, however, is that long term performance testing of these materials in a disposal setting has not been carried out. To date, the use of synthetic materials in disposal facilities has been confined to temporary capping operations.

Rock and aggregates are an essential part of most closure systems, especially caps. These range from sands and gravels, employed as grading materials, to large cobbles used as intrusion barriers against animals and plant roots [30]. They also play a part in drainage layers within caps, in capillary breaks [30, 34, 35, 37] where the choice of particle size is important and as fill material for drainage blankets.

Vegetation can play an important part in the performance of a capping system, specifically in reducing erosion and promoting evapotranspiration which, in turn, will reduce infiltration into the cap [21, 22, 37–40]. Ideally, the choice of vegetation species for the cap can be based on the following considerations:

- the plants are not deep rooted so they do not threaten the integrity of the resistive layer,
- the plants' root system will provide maximum stabilization to the cap material, thus reducing erosion,
- the plants' ability to survive the range of climatic conditions that the repository will experience,
- the plants' ability to maximize evapotranspiration throughout the year, e.g. evergreen, not deciduous.

3.3. FAILURE MECHANISMS

All engineered features and structures will at some point fail to carry out the function they were designed to perform [21, 22, 39, 40]. This failure may be a sudden catastrophic one, resulting from stresses outside the design envelope and tolerances of the structure, or it may be a gradual reduction in performance over a period of time. This section will discuss the failure mechanisms that the engineered structures and features of near surface disposal facilities are susceptible to. There are a number of mechanisms by which closure features may fail [21, 39, 40], the major ones being:

- erosion,
- intrusion (human, animal and plant),
- weathering,
- differential settlement and subsidence,
- clogging,
- pressurization due to gas generation,
- chemical and microbial attack,
- ecological succession.

3.3.1. Erosion

Erosion is the loss of cap material through the action of rain, surface water run-off, or wind. It is a major concern for soil caps where the principal method of preventing erosion is the establishment of a vegetation cap and control of surface slopes. Erosion may promote water ingress through physical removal of cap soil and/or expose the active components of the barrier, such as the conductive or resistive layers to weathering, which may further reduce their effectiveness. Rainfall erosion is generally a slow process on vegetated caps and surface slopes of low grade (e.g. maximum slopes of less than 5%). USEPA [21] also recommends that erosion rates of less than 0.4 mm/yr which equates roughly to 4.4 metric tons/ha/yr (assuming a soil density of 1 g/cm^3) be achieved in order to maintain the integrity of the cap over long time frames. Wind erosion may also be a problem in arid regions where fine-grained soil is used for the cap and the vegetation cover is sparse. Cobbles and gravel have been used in controlling erosion on the cap surface, but a properly constructed vegetation cover alone can be very effective for erosion control. Both run-off and wind erosion may be enhanced by mechanical and physical disturbances (i.e. human and animal intrusion, fires, etc.) of the cap, hence, it is advisable to keep these disturbances to a minimum.

3.3.2. Intrusion

Intrusion as a failure mechanism occurs when plant, animal or human actions result in a loss of integrity of one of the repository engineering features. With plants and animals, this may result in a loss of integrity of the resistive layer, or in the case of animal burrowing, may result in increased or decreased erosion and increased infiltration [41]. Animal and plant intrusion have been prevented, over the short term, by the inclusion of a cobble barrier within the cap profile [33, 38]. This works by making it difficult for small burrowing animals to extend their excavation downward into the soil profile. Cobbles can also retard plant root intrusion due to the presence of large voids which are difficult for plants roots to pass through [30, 35]. The presence of concrete or other durable barriers may also prevent the intrusion of animals and plants.

There are a number of measures which can be implemented to reduce the likelihood of inadvertent human intrusion. These include the presence of markers, showing the location of the repository, and using locally-available materials for construction so that the repository will not be viewed as a source of valuable building materials in the future. Barriers such as cobbles or concrete slabs will make intrusion by drilling and excavation more difficult.

3.3.3. Weathering

Weathering can be divided in two major processes: desiccation and freeze-thaw. Desiccation is the drying and shrinking of materials, which mainly effects clay based resistive layers and potentially bentonite based cutoff walls. It generally leads to cracking and the degree of cracking depends on factors, such as material properties, moisture content, change in moisture content and overburden pressure. Desiccation of barrier soils occurs through both direct moisture loss to surrounding soils and to the atmosphere through diffusion processes. A process that can sometimes lead to desiccation of barrier layer soil is evapotranspiration via plant roots. In arid and semi-arid locations, evapotranspiration can remove up to 100 % of the precipitation that infiltrates into cap soil [40]. The potential influence of plants on barrier soils stems from the fact that these soils, including low-permeability clays, accumulate soil moisture. During periods of moisture stress, plants will seek out this stored moisture and remove it via transpiration through the leaf surfaces.

Freeze-thaw processes can result in crack formation as a result of tensile stresses caused by the expansion as water changes phase from liquid to ice and back again. This process is most effective when multiple cycles take place and is most likely to affect clay resistive layers and cut-off walls. The depth to which freeze-thaw is a significant process depends on the prevailing climate and the material. As is the case for desiccation, there may be some potential for self healing in clays suffering from freeze-thaw cracking. A cap's resistance to climatic effects would be illustrated by the following characteristics:

- low shrinkage potential combined with a high self healing capacity,
- high moisture content of the barrier soils,
- the resistive layers installed below the depth of frost penetration to avoid freeze-thaw cracking.

3.3.4. Differential settlement and subsidence

Two important failure modes are differential settlement and subsidence. These processes can result in a catastrophic loss of performance and also promote other failure modes [2, 21, 33, 42]. Differential settlement and subsidence are defined as: (a) settlement is the consolidation of the cap, waste (including degradation) and underlying strata; and (b) subsidence is the collapse or closure of voids within the waste.

Consolidation, compression and degradation of the waste may cause settlement. The effects of settlement are generally most pronounced towards the edges of a cap. The collapse of cavities within the waste or between waste packages may also damage a cap by creating subsidence craters that result in a catastrophic displacement of cap profile layers. Rates and locations of settlement are difficult to predict and those associated with subsidence are almost impossible to predict. However, there are a number of strategies, which can be employed to mitigate the effects of settlement and subsidence. For example, it is possible to immobilize the waste in a matrix such as cement grout or slurred clay, which can support the overburden and cap. Setting standards for waste emplacement and compacting intermediate fill layers can also minimize settlement. It is also possible to delay the fitting of the final cap until initial settlement has occurred [21, 26], however, it is necessary to prevent infiltration of large amounts of precipitation into the disposal units.

Post-closure monitoring can be effective in identifying settlement and subsidence problems so that they can be corrected during the institutional phase of the repository lifetime. The effects of settlement can also be mitigated somewhat by the size of the buffer zone between the waste and the start of the cap. This material is generally used to establish the initial shape of the cap, the deeper this zone the more effective it will be in attenuating the effect of any settlement in the waste and reduce distortion. Distortion and cracking of clay layers may be reduced by the inclusion of geomembranes and geogrids into the resistive layers. These processes may also threaten the integrity of subsurface drainage systems by promoting blockage and cracking of the drains.

3.3.5. Clogging

Clogging can affect both drainage systems: sand- and gravel-based drainage layers and cobble-based plant intrusion barriers. There are a number of mechanisms that can lead to the clogging of granular drainage features. These include:

- migration of particulate materials,
- chemical precipitation,
- microbial growth,
- a combination of the above processes.

The migration of particulates can be mitigated by the correct selection of filter material to protect the drainage media. Chemical precipitation can effect granular drains by reducing the porosity. A common form of precipitate results from the oxidation of ferrous iron to form ferric oxyhydroxide. However, it is also possible that other precipitates such as calcite or siderite may also form. Microbial growth may also clog granular drains, this is only likely to occur if the waste contains sufficient organic materials or inorganic plant nutrients to support significant microbial growth.

Plant intrusion barriers can fail by clogging, if fine materials which fill the void spaces between the cobbles allow plant roots to grow through the layer. As with granular drains, this can be prevented by the correct grading of particle sizes between the soil layers and the cobble layer.

3.3.6. Pressurization due to gas generation

Under certain circumstances, it is possible for significant amounts of gas to be generated within a repository, generally due to metal corrosion or microbial degradation of the organic component of the waste. These gases are generally hydrogen, methane and carbon dioxide, but may also include hydrogen sulphide and nitrogen under specific circumstances. The generation of these gases will not be a problem provided the closure system is engineered to allow their escape. If a closure system is engineered to prevent gas from escaping, then pressurization can occur and the closure system may fail due to pressure cracking.

3.3.7. Chemical and microbial attack

Most if not all construction materials used for closure system construction will be susceptible to some form of chemical and/or microbial attack. Chemical attack will occur when some chemical species either in the ground or rain water or in the leachates from a disposal facility react deleteriously with components of the disposal system to reduce their performance. Generally, microbial attack can be considered as a specialized form of chemical attack since it results from micro-organisms, changing the chemical environment. The exception to this rule being direct degradation of substances where the microbes are using the material as a food source. Examples of this mechanism are microbial degradation of asphalts and bitumens used in closure systems.

Examples of chemical attack on concrete includes sulphate attack, which may produce cracks due to the precipitation of gypsum in the concrete, causing internal stresses. It is possible, however, to produce sulphate-resistant concretes. Steel reinforcements within concrete may also be susceptible to chloride attack and carbonation, both of which generate stresses and promote corrosion and cracks in structural concrete. Clays are also subject to chemical attacks. For example, sodium bentonite based systems are susceptible to reactions with calcium plumes from cementitious systems. These reactions form calcium bentonite which has a higher permeability than sodium bentonite.

One example of microbial attack includes the formation of sulphuric acid during the oxidation of sulphides. This has been shown to be a serious problem in concrete sewage pipes and may occur at disposal facilities if sulphides are present in the waste or generated during the degradation of the waste. Microorganisms can also promote metal corrosion, resulting in the failure of drums much faster than from normal corrosion processes.

3.3.8. Ecological succession

Ecological succession can sometimes lead to cover failure. Succession may result in plant species whose roots penetrate the resistive layer, waste, or change the evapotranspiration rate. This can generally be avoided if careful evaluation of the potential interaction of plants with the cover profile is done. Plant roots can penetrate to great depths in search of soil moisture with depths of 5 m being common in arid locations [43, 44]. Even though “shallow rooted” species are initially planted on disposal facility caps, they may be replaced later with successional species if not actively maintained over long time periods. It is generally recommended, where possible, to consider using native plant species for re-vegetating caps since they can be most effective in soil moisture use and long term persistence.

3.4. DESIGN AND SELECTION OF REPOSITORY CLOSURE SYSTEMS

3.4.1. General considerations

Selection of closure options can clearly influence the radiological risks associated with a repository as PA studies have shown. The interaction between repository closure design and PA is an iterative one, which begins with a baseline assessment, but does not take into account any engineering features. This assessment allows the primary risk pathways to be identified, which may be either groundwater transport, gaseous emissions, human intrusion, or a combination of pathways. Once the primary exposure pathway(s) has been identified, various closure designs aimed at mitigating the associated risks can be identified and then evaluated through subsequent performance assessments. Uncertainty and sensitivity analyses are integral parts of these assessments. In this way, a closure design can be developed and optimized, resulting in levels of risk that are acceptable to all interested parties. At this stage, a number of factors have to be taken into account:

- technical feasibility of the closure design,
- economic feasibility of the closure system,
- acceptability of the closure systems to stakeholders,
- viability of performance criteria required by the individual closure components over the time frames of interest,
- robustness of the closure design with regards to non-radiological factors.

All of these issues are captured in the concept of a multi-objective decision problem [45]. In this context, the design and operation of a disposal facility needs to employ the best practical means to ensure that the radiological detriment to members of the public, both before and after withdrawal of control over the facility, will be ALARA when viewed against regulatory and socio-economic factors.

The long term performance of caps is an important component of repository closure design and optimization. In most cases, the performance of engineered features will have to be estimated over at least a few hundred years. This is a problem since most performance data for relevant engineering technology only stretches over a few decades at most. There are various approaches to estimating the long term performance of engineered features, involving a combination of modelling, field and laboratory experimentation, and studies of natural and archaeological analogues for components of the cover system.

The interaction between closure system design and PA does not end with the choice of closure system design. This interaction is an iterative one that continues throughout the life cycle of a repository. As a repository moves from the design to the construction phase, further information will become available, for example, through materials testing, which can be incorporated into revised performance assessments. These assessments will allow the initial assumptions made at the design stage to be checked and refined. As monitoring data on the repository's performance becomes available, it can be used in further refining assessments of performance. Throughout this time, on-going monitoring and experimental data collection will enable the performance of the closure system to be evaluated with greater confidence.

3.4.2. Selection of closure components

There are several aspects to the selection of closure components:

- selection of the disposal facility location, if not already constructed,
- if the repository is constructed, selection of individual components, i.e. cap, cut-off wall, drainage system, or markers,
- compatibility of closure components with the natural environment,
- ability of closure components to isolate waste materials,
- the design of the individual components chosen.

The selection of the individual components, employed in the final closure system and their specific designs, will be influenced by many different factors:

- local climate, especially the amount and type of precipitation,
- site topography,
- site geology and hydrogeology,
- nature of the waste and backfill material (radiological, chemical, physical and biological),
- cost considerations,
- availability of raw materials,
- regulatory requirements,
- the major exposure pathway, e.g. intrusion, gas or groundwater,
- international practice.

The influence of these individual factors and their interaction will be highly specific to the individual disposal facility. Thus, it is difficult to provide general guidelines. However, some common themes can be discussed. For example, if the gas pathway is a significant source of radiological risk (e.g., H-3), then a cover system which prevents gas escape may be required. On the other hand, if the nature of the waste results in significant generation of non-radioactive gases, then a cap which allows gases to escape may be required. If human intrusion is a potential route of exposure, then the closure design may use a concrete slab rather than a multi-layer cap to cover the repository. In most cases, no single factor will govern closure decisions. In the case of multi-layer cap designs, a number of repository operators have chosen designs which consider gas generation, human and biological intrusion, and water ingress (see Appendix A).

Climatic characteristics, particularly precipitation, greatly influence the types of closure systems chosen. For example, in areas where annual precipitation is low, it may be possible to use caps that take advantage of high evapotranspiration rates and engineered drainage control features to control infiltration. In regions where there is greater precipitation, this approach will not be as efficient. Consequently, a resistive layer may be needed since evapotranspiration and engineered drainage control features will not be sufficient to control all incident rainfall. The depth at which a clay layer is placed to protect it against freeze thaw processes will obviously depend on the site climate. Additionally, the regulatory authority may prescribe aspects of cover designs or may have, for example, design criteria on the permeability of the clay used to construct the resistive layer in a cap. These examples are just a few of the considerations that may enter into the design process of a closure system.

3.4.3. Analysis of closure system performance

Prior to implementing any closure procedure or activity, the operator is required to have a thorough understanding of the effects the closure system will have on the performance of the disposal facility. This entails providing input for the PA, predicting the performance of engineered features, experimentation, in-situ monitoring, physical testing, analogue studies, and mathematical modelling.

One aspect of the application of engineered barriers in any near surface disposal facility is the assessment of their long term performance [12]. The situation is easier to some extent for LILW containing mainly short lived radionuclides since the period of time under consideration is relatively short (~ 300 years).

There are a number of ways for assessing the long term performance of engineered barriers:

- experimentation,
- physical testing,
- in-situ testing,
- analogue studies,
- modelling.

3.4.3.1. In-situ monitoring

There are a number of closure system parameters that can be monitored either during the institutional control period or the operational phase of a disposal facility. This monitoring will provide data on the performance of the engineering components which can be used directly to predict long term performance of the closure system. The type of data which can be collected includes:

- settlement of interim cap and trial capping systems,
- soil moisture status in the caps,
- surface run-off and erosion,
- vegetation growth and evapotranspiration,
- biological intrusion,
- infiltration into disposal units,
- seepage through cut-off walls.

3.4.3.2. Laboratory and field testing

Laboratory testing is often used to evaluate performance characteristics of engineered barrier systems under closely controlled conditions and to simulate longer time frame performance through accelerated testing. It is difficult to extrapolate the results of laboratory geotechnical testing to field scale conditions because of the uncertainties associated with variables not evaluated in the laboratory that can influence barrier performance. Likewise, it is difficult to evaluate intact cap systems under realistic field conditions.

Closure of disposal units at currently operating facilities can provide opportunities to perform physical testing of closure features such as caps and drainage structures for the remaining operational period of the facility. For example, placing caps on completed disposal units during the operating phase and observing the development of a plant community can resolve questions pertaining to vegetation re-establishment on caps. Likewise, field-scale investigations of differential settlement can also be conducted.

The degree to which field testing can successfully assess the long-term performance of engineered barriers and their components is limited by the time periods over which experiments can be run. As a result, a number of accelerated aging techniques and laboratory tests have been used to investigate processes and properties such as concrete leaching rates, metal corrosion rates, concrete and backfill degradation rates, freeze-thaw effects, and the effects of soil shearing on permeability [2, 46, 47].

A number of experimental investigations have been extended to field scale trials [34, 35, 37, 38, 41, 48, 49] where the hydrologic response of intact capping systems has been measured. These have the advantage of allowing increased instrumentation and the flexibility of altering variables, such as the vegetation cover, precipitation regimes, soil type, and level of compaction. The advantage of studies on integrated cap systems is that they provide real time data that reflects system interaction, often under natural environmental conditions. The disadvantages are that they are often relatively small scale and short term. This leads to problems of extrapolating to larger scale and predicting long-term performance. As such, use of results from field studies are recommended to increase confidence in a particular closure design option. For example, computer models such as EPA's Hydrologic Evaluation of Landfill Performance (HELP) [50] and plant succession models have been used to make predictions over larger scales and time frames.

3.4.3.3. Analogue studies

Analogues, both natural and man-made, can provide useful information on the long term performance of engineered barriers [28, 29]. Archaeological studies can be used to investigate the performance of man-made materials over hundreds of years, or longer. Examples of man made analogues can be found for a variety of constructions materials and closure design components, including:

- vegetated soil caps,
- capillary barriers (i.e., layered soil and gravel profiles),
- drainage layers (sand and rock layers),
- cements,
- clay liners.

Investigations of pre-historic, man-made structures indicate that simple vegetated soil caps and "engineered" features can survive significant lengths of time.

In the case of cements, there are two types of analogues such as those originating from industrial use, which are only around 100 years old, to mortars, which may be up to 3000 years old. Archaeological data indicate that these materials can survive significant lengths of time, but in some cases extensive degradation has occurred.

There are several examples of the long term survival of clay materials that have been used as hydrologic barriers. For example, compacted clay with permeabilities as low as 10^{-10} m/s were used in Roman times to line aqueducts and, within the last 200 years, under dams, with failure in only a small number of cases.

An archaeological analogue that provides insight into the long term performance of clay barriers is the burial vaults in Southern China that are over 2000 years old. These structures were covered with compacted clay at the time of the burial to keep the burial chamber and its contents dry. Recent archaeological excavations of the burial vaults show that the compacted clay layers have, in many cases, been completely effective in preventing water ingress into the burial vaults. Part of the reason for the long term effectiveness of these burial systems in controlling water infiltration is that these revered sites have been actively maintained by the Chinese for over 2 millennia. This maintenance includes annual removal of all vegetation and recompacting and recontouring the burial mound surfaces.

The major problem with archaeological analogues is that there are as many examples of failures as there are successes and it is difficult to make quantitative judgments on the evidence available. Attempts have been made to carry out quantitative statistical analysis of data from archaeological structures to identify those parameters which most favour long term survival. When applied to the survival of materials in burial mounds in Japan, the structure of the most successful soil cap bore many similarities to features of current cap designs [28].

Data on the degradation of structural materials in modern buildings, dams, canals and sewers can provide information on long term stability for a variety of materials under a range of different environments. Natural analogue studies have been used to investigate materials such as bitumen [34], bentonite [29] and gravels and clay [51]. Investigations into bitumen have indicated that it is highly stable in the absence of microbiological attack [31].

3.4.3.4. Models for evaluating cover systems

Mathematical modelling is a method for assessing the long-term performance of engineered barriers [34, 37, 52–54]. The complexity and variety of modeling techniques available is of such breadth that the subject cannot be discussed extensively here. However, it is through modeling that data on the performance of barriers is incorporated into the post-closure radiological risk assessment to evaluate the performance of the complete closure system over long time periods.

Most closure technologies incorporate design features that control one or more of the processes governing the fate of precipitation falling on the surface of the disposal site. The fate of meteoric water falling on the surface of disposal facility is referred to as the water balance of the site. A simplified representation of water balance describes surface run-off and one-dimensional movement of water in the soil profile to the plant rooting depth. For net rates and amounts, the water balance equation is:

$$\delta S/dt = (P - R - ET - L)/dt \quad (1)$$

where δS is the change in soil moisture storage, P is precipitation, R is run-off, ET is evapotranspiration, L is percolation below the root zone, and t is the unit of time used in solving the equation.

Many cover design calculations can involve relatively simple hand calculations, such as the flow carrying capacity of lateral drainage layers, simple water balance calculations or slope stability calculations [17]. Some design parameters, such as maximum frost penetration depth, are empirical by nature and can be read from contour maps assembled for that purpose, and do not need to be calculated at all.

Several computer simulation models have been used in the United States to design and evaluate covers for LILW sites. Two of these, the erosion model in the Chemicals, Runoff, and Erosion in Agricultural Management Systems (CREAMS) code [55] and the water balance models of the Hydrologic Evaluation of Landfill Performance (HELP) code [50] have been widely used for evaluating closure systems. The CREAMS model has been employed to assess surface water flow and erosion/sediment transport [56]. HELP is a water budget model to apportion the precipitation and initial moisture content into estimates of the following water budget components: surface runoff, evapotranspiration, changes in snow storage, changes in moisture content, lateral drainage collected in each drain system, and leakage or percolation through each liner system. Daily, monthly, annual, and long-term average water budgets can be generated. One of the primary applications for the HELP and CREAMS models is to perform comparisons of the long-term performance of alternative cover designs.

4. IMPLEMENTATION AND CONFIRMATION

4.1. CLOSURE PLAN APPROVAL BY REGULATORY AUTHORITY

Prior to implementing any closure activities, it is important that the closure plan is approved by the regulatory authorities. The plan is required to include the changes in technology, regulations, and public concerns that have occurred since the repository was initially licensed, opened and operated, as well as a detailed design for the closure system, the relevant performance/safety assessment, construction plan, monitoring plan, past operational and environmental surveillance records and monitoring data for interim stabilization technologies used during repository operations.

4.2. REPOSITORY PREPARATION AND CLEARANCE

In preparation for repository closure, there are a number of technical operations which are required. These include:

– clearance and decommissioning of existing building and other structures,
– if necessary, removal of interim measures such as temporary caps,
– selection of materials and provisions of materials handling areas,
– infrastructure changes to allow the delivery of construction materials.

4.2.1. Clearance and decommissioning

Any operational repository will have a number of buildings and structures, which will require either demolition or shut down prior to closure. Buildings at the disposal facility can be simply demolished or removed provided they have no radiological contamination. It is possible that the final materials disposed of at a repository may result from the shut down of buildings and structures used during the operational phase. If this is the case, provision needs to be made to ensure enough spare capacity is available at the repository to allow for the safe disposal of this material.

Drainage features may also require decommissioning prior to disposal facility closure. Many drainage features, which are present in an operational repository, may not have the required characteristics or performance life to be of any use in the final closure system. Drainage features may also produce significant void space beneath a repository and consequently may pose a subsidence hazard if they are unable to withstand the overburden place upon them after closure. If these features are not required, one option is to fill or seal them by grout injection. If they are to remain in service, then it may be possible to fill them with a granular material such as aggregate to allow them continued function under increased overburden. Special precautions need to be taken during the repository construction phase to ensure that it is technically possible to backfill these features later.

4.2.2. Removal of interim closure measures

Depending on decisions made by responsible parties about the appropriateness of interim closure actions for final closure; temporary caps or cutoff walls, may need to be removed prior to construction of the final closure system. If this is the case, workers need to be protected from unacceptable radiological risks. Ideally, the removal of these features would have been included in the initial design and planning stages to ensure that minimal radiological risks are presented to the construction work force. It is possible that the responsible authorities will decide to accept interim closure activities as an acceptable component of the final closure of the repository. In that case, close co-operation between all interested parties during initial licensing and operation phases of the facility will maximize the potential use of interim measures as a part of the final closure system.

4.2.3. Materials selection and handling areas

Repository closure systems may require large amounts of various construction materials such as aggregates, cement, bentonite, natural clay, asphalt etc. The choice of these materials can have a significant impact on the economics of a closure system design. Where possible, using natural materials available locally at the time of the closure can be the best solution from an economic, or even technical, perspective. Displaced or spoil materials may be candidates for construction materials if their specifications are suitable. Local natural materials have the added advantage that their proximity to the repository means that transport costs will be reduced. Many disposal facilities will not require closure for decades, however, availability of local materials is necessary for their final closure.

Any large construction project requires areas set aside for the use of contractors and materials storage and handling. These areas will house construction machinery and other equipment such as concrete batch plants and associated silos. As with construction machinery, there will also be a requirement for a materials handling facility where material can be off loaded and segregated prior to use during construction. Both these areas may require some preparatory construction work such as pads for equipment. The building and siting of the areas needs to be performed so that impacts on the local environment and populations are mimimized. Noise and dust abatement are also considerations, although closure operations probably will not impact the environment appreciably more than any other similarly sized construction project.

4.2.4. Infrastructure changes

The size of the project associated with closure may be such that large quantities of construction materials need to be delivered to the repository. If so, some logistical planning can help minimize disruption to the local road and rail network. It is possible that it will be necessary to construct new rail siding, road junction or even to upgrade the local road network to allow the efficient delivery of construction materials.

4.2.5. Scheduling

Final closure activities are planned carefully to take advantage of human and materials resources and weather. In areas with extreme climates, certain closure activities are seasonal activities. For example, installing impermeable geomembranes in summer at a facility located in a hot desert is impractical during the day. Likewise, compacting clay cut-off walls in the extreme north in winter or early spring is also impractical. Attention to these matters will significantly improve the efficiency and quality of closure operations.

4.3. CONSTRUCTION OF CLOSURE SYSTEM

The major tasks of construction of a closure system are:

- verification by soil testing that underlying materials are ready to be capped,
- excavation and preparation of soil material,

- placement of monitoring systems,
- placement of engineered barrier systems,
- installation of drainage control features,
- revegetation,
- quality control.

4.3.1. Verification and testing of soils

Prior to installing any closure feature, it is important to establish that the waste form and backfill possess sufficient bearing strength and compaction characteristics. If the waste and backfill are not sufficiently stable, the cap and other closure features may undergo early failure such as differential settlement. Design engineers need to review test results to assure that the capping and closure methodology will not be compromised.

4.3.2. Excavation and preparation of soil material

Material preparation can be accomplished by blending or modification with additives. Soils can be modified with additives such as lime, bentonite, cement or asphalt as necessary. Soil amendment is typically performed to enable the use of indigeneous soils rather than imported material. Prior to using the blended or modified soil mixtures, tests have to be run to verify that the mixture will meet the design specifications.

4.3.3. Placement of monitoring systems

Provisions for monitoring repository performance, such as gas generation, percolation of water through the barrier system, and leachate production, may need to be installed during construction activities. Careful planning and special construction procedures may be necessary to prevent damage to delicate components of the monitoring system. Some monitoring systems, such as boreholes for monitoring gas and liquid migration, can be installed after construction activities have ceased. However, special consideration is needed for evaluating the effects of placement of monitoring systems on the performance of multilayered caps. Technical guidance documents are available for assisting in the design and placement of monitoring instrumentation in waste disposal facilities undergoing the closure process [21].

4.3.4. Placement of engineered barrier systems

Soil placement — Soil or material placement is the most critical phase of the construction process. It is important that soils are spread evenly to achieve a specific minimum thickness, and carefully supervised to avoid disturbance of the underlying layer of cap. As an extra precaution during construction over the top of the geomembrane layer, placement of a protective layer of soil or a fine mesh geogrid above the geomembrane is usually recommended. If the cap will be placed over a disposal unit stabilized with concrete, placement prior to solidification and curing is inadvisable. Because solidification and curing may take several days or weeks, this period needs to be noted in any construction schedules or accompanying specifications.

Soil compaction — Standard construction procedures used in building and roadway earthwork also are used for construction of caps. It is critical that the integrity of the cap layer beneath the working surface be protected from damage at all times. A limitation on selection of equipment is the need to use equipment whose weight is within the allowable load-bearing range of the cap components.

Compaction of the soil layers is performed to increase the strength of the soil by increasing its density. Compaction is also necessary to achieve the desired low permeability. Compaction is generally required for all layers except the topsoil where compaction would prevent proper root growth.

Geomembrane installation — Geomembrane installation involves several steps including: placement of strip panels, seaming the panels with appropriate bonding or heat treatment, sealing the membrane around penetrations, and covering the geomembrane with a bedding layer. Seam failures, punctures, and abrasions are the most common problems encountered when installing geomembranes. Extreme temperatures also severely limit the efficient placement of these materials.

Drainage system — Provisions for draining excess run-off from the repository may need to be installed, as needed, to reduce the possibility of large amounts of concentrated flow and rill and gully formation on the closure cap. Drainage systems constructed from durable materials, such as rip-rap or concrete, and confined to the perimeter of the disposal facility will help ensure longevity of the system and will minimize the amount of concentrated flow over the facility. Depending on the requirements for monitoring, provision for sampling runoff, to include small settling ponds, may also be required. Controlling surface slopes to approximately 1 to 3 % and installing a good vegetation cover to reduce the amount of run-off generated by the facility can reduce the need for drainage systems.

4.3.5. Installation of drainage control features

Drainage control features are designed to convey the volume of water from the flooded areas. In the case of closure features having been integrated into the facility design and operational procedures, drainage features installed at final closure is the completion of construction of the overall drainage system. For disposal facilities that are in closure as part of a remedial action, the drainage system needs to be designed to reduce flooding or ponding, infiltration, erosion, and down gradient erosion. Concentrated flow is to be avoided unless erosion control features can be proven to be effective for the long term.

The area surrounding the disposal facility also needs to be evaluated in terms of the watershed and the potential for run-on to cause erosion. In some cases, special features, such as energy dissipation berms, flow control berms and channels, and diversion structures that are reinforced with rip-rap or lined with concrete, may be necessary.

4.3.6. Re-vegetation

The type and density of the vegetation on a disposal facility cap can play an important role in the long term stability of the repository by decreasing the potential for erosion and for soil moisture percolating downward through the cap and underlying soil materials. It is especially important that the vegetation cap consist of a varied mix of species, at least some of which are actively transpiring during the entire time when soil moisture recharge is occurring. The higher the transpiration rate is during this period, the lower the potential for soil moisture movement downward into the disposal unit. Properties that are desirable for selecting species for vegetating caps include:

- representative of the native vegetation cap in the area to reduce the effects of plant succession,
- long lived perennial species,
- resistant to fire, drought, and disease,
- provide maximum potential to remove soil moisture via evapotranspiration.

Despite the obvious benefit of plant roots being distributed throughout the cap profile (i.e. soil moisture removal), there is concern about the potential of roots penetrating into engineered barriers or buried waste. Selecting “shallow rooted” species is often recommended to mitigate potential impacts of plant roots on engineered compacted soil barriers. Because plant root distribution in the soil profile is largely determined by available moisture, “shallow rooted” species still have the potential to penetrate a few to several meters into the soil. Synthetic membranes or greater overburden depths can be used to help to control plant root effects on the integrity of engineered barriers. The cap root zone needs to be thick enough to capture and store all of the precipitation that infiltrates into the soil. This will help confine roots to the vegetated layer since plants only penetrate downward into the soil to seek water. The benefits of extensive plant root distributions throughout the cap profile point to the need to optimize vegetation cap features with other design components, thus maximizing water management in the disposal unit.

4.3.7. Quality control

The principal activities of a QC programme for the construction of the closure system include [8]:

- screening incoming materials,
- construction and field testing of test controlling construction processes,
- controlling grades,
- protecting sensitive closure components such as geomembranes,
- assembling and installing geo-membranes and engineered components,
- observation of construction procedures,
- measurement of final cap layer thicknesses,
- surveying of final grades.

The QC inspector is expected to be thoroughly familiar with the specifications to ensure that materials and installation procedures conform to contract standards. There are several areas of closure system construction that require specific procedures for quality control. These areas include:

- *Materials grading:* Grading and sorting of materials is recommended prior to their application and use in a closure system.

- *Compaction control*: Compaction control is necessary to assure that individual layers of the cap are stable enough to support overlying layers or that permeability standards are achieved.

- *Geomembrane installation*: Geomembranes typically are installed as low-permeability layers over large areas, requiring the use of welding to seal the seams. Any improper weld that results in a seam that is not completely sealed can result in a preferential pathway for infiltration.

– *Joints and Interfaces*: Where different materials are joined, a potential exists for problems caused by different permeabilities, strengths, and other properties. Controls are required to ensure that joints and interfaces are properly connected.

4.4. CONFIRMATION OF CLOSURE SYSTEM

The confirmation process consists of several activities that include repository inspections, data collection and management, and presentation of information to the appropriate regulatory body to gain final approval for repository closure. This process is most intense during the early stages of closure, or during the period immediately following operation. If the repository performs as designed during this short period following operation, it is then placed into an institutional control phase. An important part of the institutional control period is to demonstrate by periodic monitoring and observation that the repository is functioning as intended to isolate waste from the biosphere. The level of activity decreases at latter stages of the institutional control period as confidence in the repository's performance increases based on the results of post closure monitoring and observation. The eventual goal of closure is to have enough confidence that the repository will not ever represent a significant risk to human health so that the land may eventually be used for other purposes. The following activities request important features of the confirmation process.

4.4.1. Cap systems inspection and maintenance

A maintenance programme is required to ensure the continued integrity and effectiveness of the cap. Preventative maintenance work scheduled periodically for a period of time (2-3 years) after cap installation will help to prevent loss of vegetation, erosion, and gully development.

Regularly scheduled maintenance inspections need to be implemented to provide early warning of more serious problems that would impact cap integrity, such as cap subsidence, slope failure, leachate production or gas migration, or deterioration of the drainage system.

4.4.2. Monitoring during the institutional control period

Monitoring during the institutional control period, if properly performed, serves the purpose of ensuring the physical integrity and security of the repository, as well as identifying potential health, safety and environmental problems. Additionally, monitoring of the key components of the system can be used to validate predictions based on PA models to provide confidence in future repository performance.

Post-closure monitoring requirements are generally dictated by the regulatory authority and depend on the physical. biological, and chemical features unique to the disposal facility and surrounding area. A discussion of the post-closure monitoring requirements for a disposal facility can be found in [3, 14, 24].

The design of the monitoring system is usually considered in context of the intended use of the data and the level of maintenance required. It is required to balance information needs with the requirement to keep maintenance to a minimum. Simple, robust, and reliable systems are preferred when designing a long-term monitoring program for closure. If used properly, monitoring data not only demonstrate compliance with regulations, but lend confidence to predictions about the future performance of the repository.

Special care is required to integrate the monitoring and closure systems so that neither system's intended purpose is compromised. For example, constructing a low-permeability, multi-layer cap may be necessary to adequately contain waste. However, if the design of the facility calls for that cap to be penetrated by monitoring instrumentation and sampling access points, the risk increases that those penetrations can become preferential pathways for moisture and contaminant movement. In the case of tritium especially, such penetrations would be direct conduits to groundwater, allowing rapid transport. Not only would preferential pathways compromise the closure system's performance, the monitoring data obtained could be biased.

In principle, the design of the repository closure system does not rely on post-closure surveillance. However, it may be necessary to include some maintenance for some parts of the facility such as the water collection and treatment system. Post-clsoure monitoring and surveillance programmes may include:

– monitoring of air, vegetation, surface water and groundwater,
– inspection of surface conditions and drainage systems,
– surface maintenance,
– intrusion surveillance.

If monitoring methods and locations are properly designed, contaminant monitoring data can be used to establish the validity of the relevant performance assessment procedures, to serve as a basis for modifying those procedures to better reflect repository conditions, and to assist in developing corrective actions, if they become necessary.

A variety of hydrologic monitoring techniques can be used to measure conditions at the repository including instruments for measuring soil moisture in cap and backfill soils, lysimeters for measuring percolation, and soil solution and pore gas samplers emplaced at strategic locations in the disposal unit and immediate area for directly measuring contaminant transport. Many of these techniques are amenable to automated data collection and data management.

4.4.3. Records management

It is the responsibility of the waste management authority and the regulatory agency to ensure that the appropriate documents and records are stored in appropriate archives. After closure, the authorities may need to access the archive of repository closure records to carry out periodic reviews of safety, or to assess system performance in the event of higher than expected contaminant release rates. It is generally advisable to keep records about the waste properties and waste disposal facility at several locations, both by waste managers and by the national authorities. The most important records to be kept are those relating to:

– geographical location of the repository,
– chemical and physical properties of the wastes,
– design of the repository,

- the final performance assessment,
- operational records of the repository,
- closure system construction records,
- regulations,
- general information pertaining to public consultation.

The QA plan for closure is developed to provide a detailed description of records management and records archiving [57].

4.4.4. Closure approval and transfer to post-closure phase

Data demonstrating acceptable repository performance during the institutional control period serve as the basis for obtaining regulatory approval for final closure. After regulatory approval of the closure plan, the disposal facility and associated records are transferred to the regulatory and national authorities.

5. SUMMARY AND CONCLUSIONS

This report reviews closure concepts, requirements, and components of closure systems for near surface disposal facilities accommodating low and intermediate level radioactive waste. It discusses various issues and approaches, including regulatory, economic, and technical aspects, that are important in the planning, design, and implementation of disposal facility closure. In particular, the technical aspects encompass structural components (i.e. caps, cutoff walls, drainage system, markers, materials), failure mechanisms, performance assessment and implementation of the closure system. Also presented in the report are examples of closure techniques used and/or considered by Member States. The information and concepts presented in this report apply equally well to formerly used and shut down near surface repositories and to current and planned repositories.

The closure system selected for a particular disposal facility is very much influenced by repository design and site-specific factors. Due to the relatively long lifetimes required of repository closure systems, designs are required to not only incorporate good engineering principles, but also take into account the long term interactions between the physical, biological, and chemical factors that are likely to affect the integrity of the closure system. No single closure system will work for all repositories. Some repositories may require complex engineered closure systems, while very simple, inexpensive designs may be entirely adequate at other repositories. In general, the functioning of the closure system is determined not by the characteristics of the individual barriers, but by the integrated system, consisting of the constituent barriers, drainage features and vegetative cover.

Construction activities and materials for repository closure are expected to conform to accepted engineering standards to ensure that the designs are consistent in quality with the assumptions used in the performance assessment modeling. Rigorous QA/QC and specialized construction techniques and procedures are required for the design and construction of closure systems.

There are uncertainties related to long-term performance of closure systems. The models for cover failure in current performance assessment models are largely empirical and poorly validated. Cover system designers deal with long-term degradation processes that lead to barrier failure by applying margins of safety to calculations representing as-built systems. There is a need to bridge the gap between “as-built” design calculations and the empirical assumptions that enter into performance assessment models. Such efforts would improve confidence in performance assessment results and provide closure system designers with improved design criteria.

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Appendix

CLOSURE PRACTICES IN MEMBER STATES

CZECH REPUBLIC

DUKOVANY REPOSITORY

The repository at the Dukovany site is a structure located above the land surface. It consists of two double-rows of reinforced concrete vaults. Each double-row has dimensions 38 × 160 x 6 meters and contains 2 × 28 vaults. The internal dimensions of each vault are 18 × 6 × 5.4 meters.

The repository serves for reactor wastes from the Dukovany and Temelin nuclear power plants (NPPs). Its capacity is 55 000 m^3 or 130 000 drums.

The repository is a fully engineered facility with multiple barriers. The first engineered barrier is the waste form (in the case of waste from the Dukovany NPP, the waste form is mainly bitumen, but concrete and glass are also considered as suitable solidification products). The second barrier is the container (a 200 litre steel drum or a HIC container), whereas the third consists of cut-off reinforced concrete walls with asphalt-based hydro-insulation. The fourth barrier is a cap which should protect the vaults against infiltration of rainwater and should serve also as an intrusion and erosion barrier. The fifth barrier is a drainage system around the repository which is composed of layers of gravel and sand.

The void space in drums around the waste is filled with specially composed grout. Such waste packages are emplaced into the disposal vault, which is covered by pre-fabricated panels. Thereafter, joints between the panels are sealed and a provisional coverage added; the final cover, however, will be constructed only over the whole row of 28 vaults, until all vaults are filled with waste. The final cover will encompass the following components:

- reinforced concrete pre-fabricated panels (500 mm),
- cement overcoat (30 mm),
- insulation foil,
- concrete layer for cap levelling (5–150 mm),
- layer of asphalto-propylene concrete (150 mm),
- soil (450 mm),
- geotextile foil with topsoil (top surface vegetation).

FRANCE

THE CENTRE DE LA MANCHE DISPOSAL FACILITY: ENTERING INTO THE INSTITUTIONAL CONTROL PERIOD

1. Introduction

The Centre de la Manche disposal facility, created by decree in 1969, is the first French near-surface radioactive waste disposal facility. It lies at the northwest end of the Cotentin peninsula, next to the COGEMA-La Hague fuel reprocessing plant (Figure A.1). The Centre de la Manche facility occupies an area of about 150 000 m^2. Its operation was terminated in late June 1994 with about 500 000 m^3 of packages disposed of. Operating feedback from the Centre de la Manche was used to design the second French disposal facility, located in the Aube, which has been receiving LILW since 1992.

Since the end of the operating period, ANDRA has been preparing the statutory files to prepare the Centre de la Manche for its entry into the institutional control period. A new government decree will set the framework in which the Centre will evolve in this period. The regulatory process includes the filing of an application with the ministries concerned, containing a file with the requisite statutory documents, including an impact study of the facility on its environment as well as a hazard study. The file will then be submitted to a public inquiry, an essential informative period of the project designed to make a compilation of criticisms and suggestions from the public. In support of the application, a safety report has been sent to the Nuclear Installation Safety Directorate (DSIN) for a decision on the admissibility of the application. Recently, the Group of experts appointed by the DSIN which examined it has come out in favor of the creation of a new basic nuclear installation (i.e., a new government agency) for the institutional control period. A draft decree will then be submitted to the approval of the Interministerial Commission for Basic Nuclear Installations.

This process, initiated in 1994, is nearing completion.

2. Developments in techniques and management rules of the Centre de la Manche

In 1969, the Centre de la Manche was run by a private company, INFRATOME, which assumed full responsibility for the transport, conditioning and disposal of all LILW. The safety and the radiation protection of the Centre was regulated by the French Atomic Energy Commission (CEA) through a technical liaison committee.

At the start, and according to the activity of the waste packages, the waste was either buried in earthen trenches or placed in trenches in concrete bins. Rainwater was collected in a pit which was conveyed by gravity to a retention tank. Depending on the level of radioactivity, it was either sent to the Sainte-Hélène river or discharged into the sea via COGEMA's installations. After one year of operation, the ordinary earth trenches, which were deemed unsafe, were abandoned in favor of "platforms". The soil was leveled, covered with a layer of local materials and a bitumen emulsion. These "platforms" were equipped with a water drain. The packages were stacked on the platforms to form mounds. To guarantee overall mechanical strength and to facilitate disposal operations, the framework of the structures was built of concrete blocks containing the waste arranged stepwise on the edge of the structure, bounding internal compartments. Metallic drums were placed in these compartments, covered by a plastic sheet and a layer of soil. Starting in 1975, the voids between the packages were filled with gravel. The plastic sheet was eliminated in favor of a layer of gravel and soil. The concreted trenches consisted of concrete bins in which the packages were backfilled with sand. The presence of water was detected in one of these trenches in 1972. The sand was replaced by cement to guarantee better sealing of the structure.

In 1978, the CEA, which assumed sole management of the radioactive waste for one year, created the Waste Management Office (OGD — Office de Gestion des Déchets), which was charged with preparing the formation of ANDRA. In 1979, the Central Service for the Safety of Nuclear Installations, which examined the safety report, authorized the OGD to continue the operation of the disposal facility subject to compliance with technical requirements in addition to those of the 1969 decree. In particular, the waste had to be fully described and its characteristics had to meet the requirements and conditions set by the operator. For example, they could not contain free liquids, nor give rise to exothermic reactions. All wastes emplaced had to be above the water table. The site and its environment had to be kept under permanent surveillance.

ANDRA was formed by a decree in 1979 within the CEA. The underlying principle of the disposal facility has since then been based on a "multi-barrier" system: the first barrier is the package, and the second the structures placed around it. Through its retention properties, the site played the role of the third barrier. Concerning the packages, one of the first actions was to work alongside the waste generators to promote radioactive waste conditioning and disposal specifications. About 150 different types of package existed at the time, and they were standardized. At the same time, ANDRA established a policy of "super-controls", which consisted in sampling the produced packages at random to check the declaration of the waste generators.

The construction of the structures, which represented the second barrier, was improved. The solid earth trench, which had been built in 1969, was dismantled. The packages were retrieved, reconditioned and disposed of. The seepage water collection system was separated in 1980 in order to collect separately rainwater and water which percolated around the waste packages. Starting in 1981, the "platforms" became host structures of reinforced concrete. These structures were built to withstand earthquakes and to collect rainwater efficiently. The concrete trenches, which were buried, were abandoned and replaced by monoliths, which were prefabricated reinforced concrete bins or concrete blocks. They were built on the host structures. One-story structures were thus created. The lower level consisted of a raft on which the monoliths containing the waste drums were positioned. A second raft was placed on the monoliths, supporting the waste packages arranged in a mound. To prevent line breakage and to avoid the use of pumps liable to failure, a separate underground gravity water recovery system was built in 1982.

New technical requirements were issued in 1985, enabling continued operation of the Centre. The new technical requirements limited the quantity of radionuclides that could be disposed at the Centre de la Manche and stipulated the requirements for designing and building disposal structures. The waste had to be covered by an authorization procedure according to the specifications. The disposal areas had to be protected from rainwater by means of a suitable and effective cap.

Construction of structures at the Centre de la Manche continued up to 1994. Between 1991 and 1997, ANDRA constructed a cap to cover the disposal areas; the cap was designed to isolate the wastes from infiltrating water, and to prevent plant, animal and human intrusion. This cap plays an important role for the safety of the public and the environment (Figure A.1).

The cap has been designed to consider factors as embodied in the following performance criteria:

- **Impermeability** — The amount of precipitation penetrating the cap and coming into contact with the waste must be very low (< a few liters/m^2/yr) to prevent radionuclide leaching and subsequent migration.
- **Durability** — The properties of the cover have to be maintained over extended times.
- **Protection** — The causes of cap system failures are:
  - the effects of changing seasonal temperature,
  - erosion,
  - settlement,
  - animal intrusion, microbiological and chemical action.

From the bottom upward, the cap consisted of (Figure A.2):

- a shaping layer of compacted coarse-grained materials (based on shale and sandstone) designed to impart a slope profile to the cap and to enhance the tightness of the system by its low permeability (the thickness of this layer is between 0.5 and 10 m). This layer has two other functions: protection of the membrane from the eventual waste settlement and biological barrier;
- a drainage layer of fine-grained sand designed to serve as a support for the bituminous membrane and to collect any seepage water in case of membrane failure (the thickness of this layer is 0.2 m);
- a bituminous membrane sealing the multi-layer complex. The goal is to limit flow through the cap to a few L /m^2/yr (the thickness of the membrane is 5.5 mm);
- a fine sand drainage layer designed to prevent permanent head pressure of the membrane and to collect seepage water transiting through the biological barrier (the thickness of this layer is 0.3 m), during the cover construction, this layer isolates and protects the bituminous membrane from construction equipment;
- a layer of compacted coarse-grained materials, designed to regulate the arrival of seepage water on the membrane and, above all, to protect the membrane from attack by roots and burrowing animals (the thickness of this layer is between 1 and 2 m);
- a layer of plant soil (0.3 m thick). The two main functions of this layer are erosion control and evapotranspiration.

The outer appearance of the "factory roof" type cap planes which promotes the runoff is a succession of sloping from east to west, with a 6 to 14 % inclination. On the edge of the facility, a system of panels stops at the upper limit of the structures. Beyond this, the cap is placed in a slope with a grade of 2.3/1 (horizontal/vertical) up to a peripheral road surrounding the covered area and terminating towards the facility boundary in a 3/2 slope. The same limits imposed the construction of support walls in the north and east.

Its design allows effective rain and seepage water management today through four separated networks (Figure A.2):

– a surface network collecting runoff from the cap. Owing to their sources, these waters incur no risk of radioactive labelling in a normal situation;

– another network collects the seepage water flowing to the biological barrier of the cap and on and possibly under the bituminous membrane. Examination of the feedback indicates that the water collected by this system incurs a risk of slight tritium labelling (connected with gas transfers from the disposal structures);

– the separative water collection system (SWCS) gathers the water drained and collected at the base of the disposal structures, after infiltration through the waste packages (i.e., a leachate collection system). This system incurs a risk of radioactive contamination;

– a complex deep drainage system is positioned at the base of the buried installations of the Centre de la Manche. This network is not in direct contact with the waste packages. Nonetheless, since it is at a lower altitude than the waste disposal level, it incurs a risk of radioactive contamination.

Depending on their radiological properties, these waters are sent to two outlets in a building, called the "basin building". ANDRA then transfers these waters to the adjacent COGEMA plant which processes them. Waters incurring no risk of radioactive contamination in normal operation are discharged into the Sainte-Hélène river after monitoring. Water liable to be radiologically contaminated is intended for direct discharge into the sea.

3. The institutional control period

ANDRA proposed a phasing of institutional control in three periods:

The first period will be a *period of highly active surveillance*, to last about five years and designed to assess the satisfactory operation of the cap in particular. The second period will be a *period of active surveillance*, to last between 50 and 100 years. ANDRA's presence at the Centre is necessary to ensure the monitoring and maintenance of the facility, as well as environmental surveillance. Its task will be to confirm that any change in the cap continues to meet the requirements and to investigate any further arrangements needed for its strengthening.

Remedial alternatives that would be considered throughout this period include:

– maintenance of the cap without change,

– repairs to the present cap,

– major reworking of the present cap (replacement of the membrane, repair of the slope grades, for example),

– installation of a new cap.

The third period will be a *period of passive surveillance*, during which ANDRA will conduct reduced surveillance of the Centre and its environment, but in which complete abandonment of the Centre will not incur unacceptable consequences for the environment. The transition to this period can only succeed after the verification of certain assumptions on the behavior of the Centre over the long term, and the possible implementation of technical improvements aimed to supplement the present containment systems with passive arrangements, which are simple and reliable over the very long term.

However, the institutional control period will ultimately have to end. It is therefore important to take the necessary measures to restrict the nature of the structures or equipment to be installed there. This is why the memory of the site will be preserved as long as possible by the archival of major data in a lasting paper record. In this respect, an archive box containing the major documents is currently being prepared. It could contain a description of the packages and of the inventory, a description of the installations, a drawing of the structures and a qualitative analysis of the risks incurred by the facility, so that the risks associated with any future use of the site can be clearly identified. This box will be archived in the local (town halls, land survey) regional (prefecture, general council) and national (ministries, national archives, ANDRA) administrations. Further restrictions to prevent intrusion at the site should be established during the active institutional control period.

4. Surveillance of the centre and its environment

The surveillance of the Centre is an indispensable tool for managing the safety of the Centre de la Manche. It relies on a series of measures stretching into time and designed to:

– confirm the observance of the statutory requirements, particularly concerning releases,

– detect any abnormal situation or development so as to locate and identify its causes (This means continued vigilance covering any abnormal development of the facility),

– estimate the quantities of radioactive and chemical substances liable to exit the facility and identify the pathways,

– contribute to the knowledge of the activity release mechanisms.

This plan was drawn up on the feedback accumulated since 1969 in terms of surveillance, operating procedures, incidents, technical events and the study of the various mechanisms involved, and also from the analysis of the risks of the installation. It accounts for the statutory provisions imposed in terms of release control.

It is based on three major guidelines:

– surveillance of the tightness of the cap. In practice, the tightness of the cap is monitored by visual and topographic inspection, by sampling the membrane, by hydraulic monitoring of the different networks of the Centre, and by radiological and chemical surveillance of the groundwater and the waters of the SWCS;

– surveillance of any releases from the disposal structures, into the networks and to the groundwater. Water in the networks is subjected to radiological and chemical measurements at the two outlets of the basin building. The groundwaters are monitored by radiological and chemical measurements via 60 piezometers. These measurements also serve to confirm the position of the groundwater table in relation to the disposal structures and to identify the groundwater flow paths. Piezometric high and low water maps are charted every year. Radiological and chemical measurements are also taken in the water of the three neighboring streams (Sainte-Hélène, Grand-Bel, Rotheures) and in the sediments;

– radiological and chemical surveillance and monitoring the volumes of incurred waters transferred from the Centre to the COGEMA La Hague reprocessing plant.

Atmospheric radiological tests, measurements of ambient radiation, measurements on plants and rainfall measurements are also conducted.

More than 10, 000 measurements are taken annually. They are checked by the Office for Protection against Ionizing Radiation which reports to the Health Ministry. Moreover, the main results of radiological and chemical surveillance of the Centre and its environment are presented quarterly in an information booklet for the public.

The interpretation of the measurement results is not based on thresholds or alert levels, but on changes in the parameters measured, seen against a reference state of the installation and its environment. This interpretation relies on a number of simple criteria established in line with the main conceivable accident scenarios. For example, three criteria of the "absence, appearance or change in roof deformations" type are associated with the situation in which a large local leak of the membrane occurs.

5. Recent performance monitoring data

Since the cover cap has been installed, measurements show a sharp reduction of the water percolating through the disposal cells. For example, in 1992, the volume of water collected in the separate water collection system (see Figure A.3) was about 40 000 m^3. However, in 1998, the volume collected by the SWCS had decreased to about 300 m^3. A commensurate decrease in radioactivity in the leachate was also noted. For example, tritium releases decreased from 2, 620 GBq in 1992 to 24 GBq in 1998. The timing of these decreases in water and radioactivity collected by the SWCS correlate well with the beginning and completion of the construction of the cover cap. Cap construction was started in 1991 and completed in 1997.

6. Research and developement

The design of the cover cap of the Centre de la Manche required some specialized studies to include:

- comparison of performance between several types of geomembranes (bituminous, PVC, High Density Polyethylene), particularly in terms of durability and deformability,
- comparison of performance between several drainage materials (PVC, High Density Polyethylene),
- concrete durability,
- historical studies of slope stability using old building sites and dikes,
- construction of a clay cover demonstration plot near the Centre de la Manche site.

7. Cost elements

The total cost of the closure system in the Centre de la Manche is about 95 million US dollars. This cost includes construction of the cover cap, the monitoring system (including monitoring up to the next 5 years), the visitors' centre, etc. The cost of the monitoring during the institutional control period is estimated to be 2–3 million US dollars per year over the next 5 years. The monitoring cost will include measurements, special studies, and manpower.

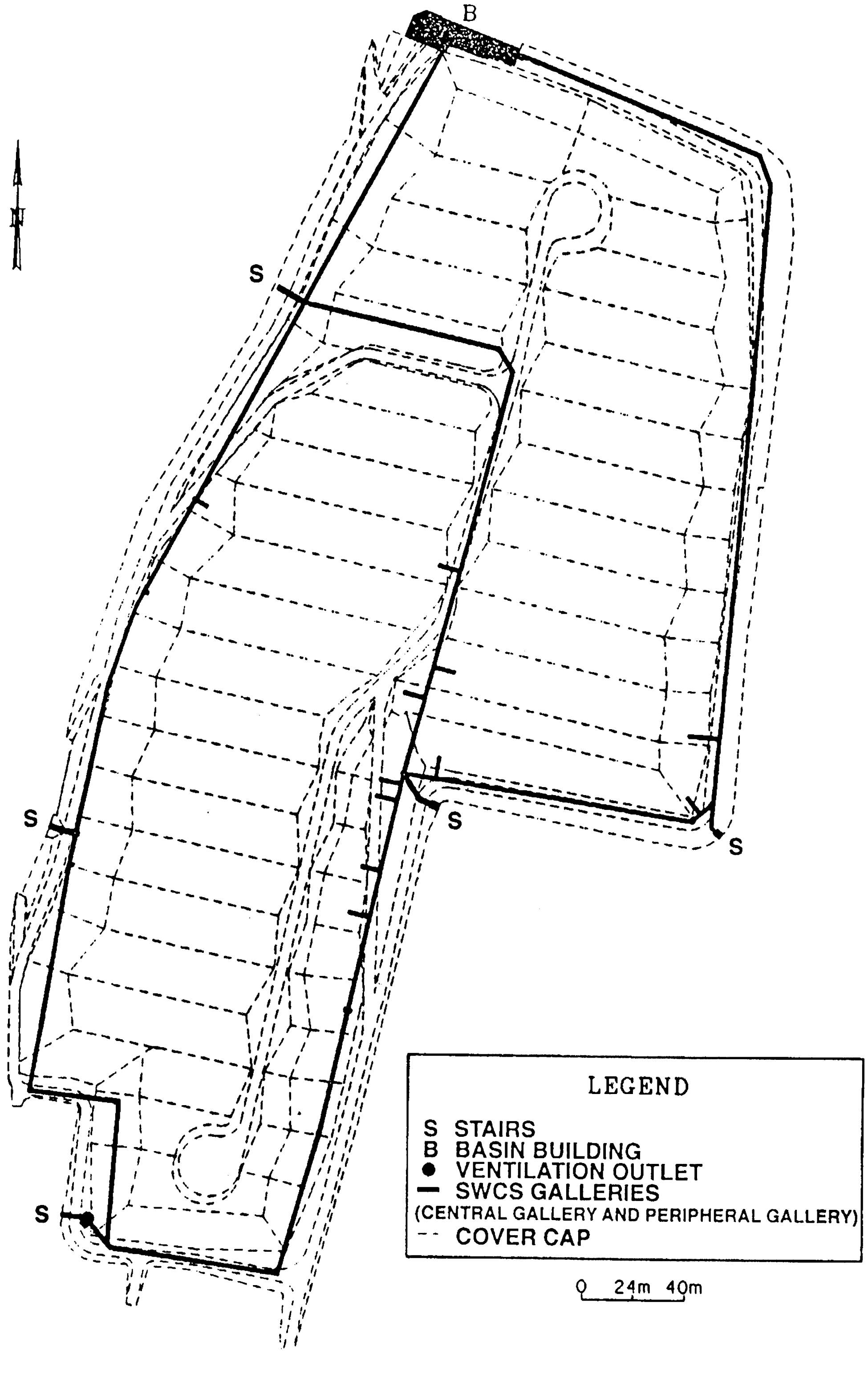


FIG .A.1. Plan view of the Centre de la Manche with cover cap and topography.

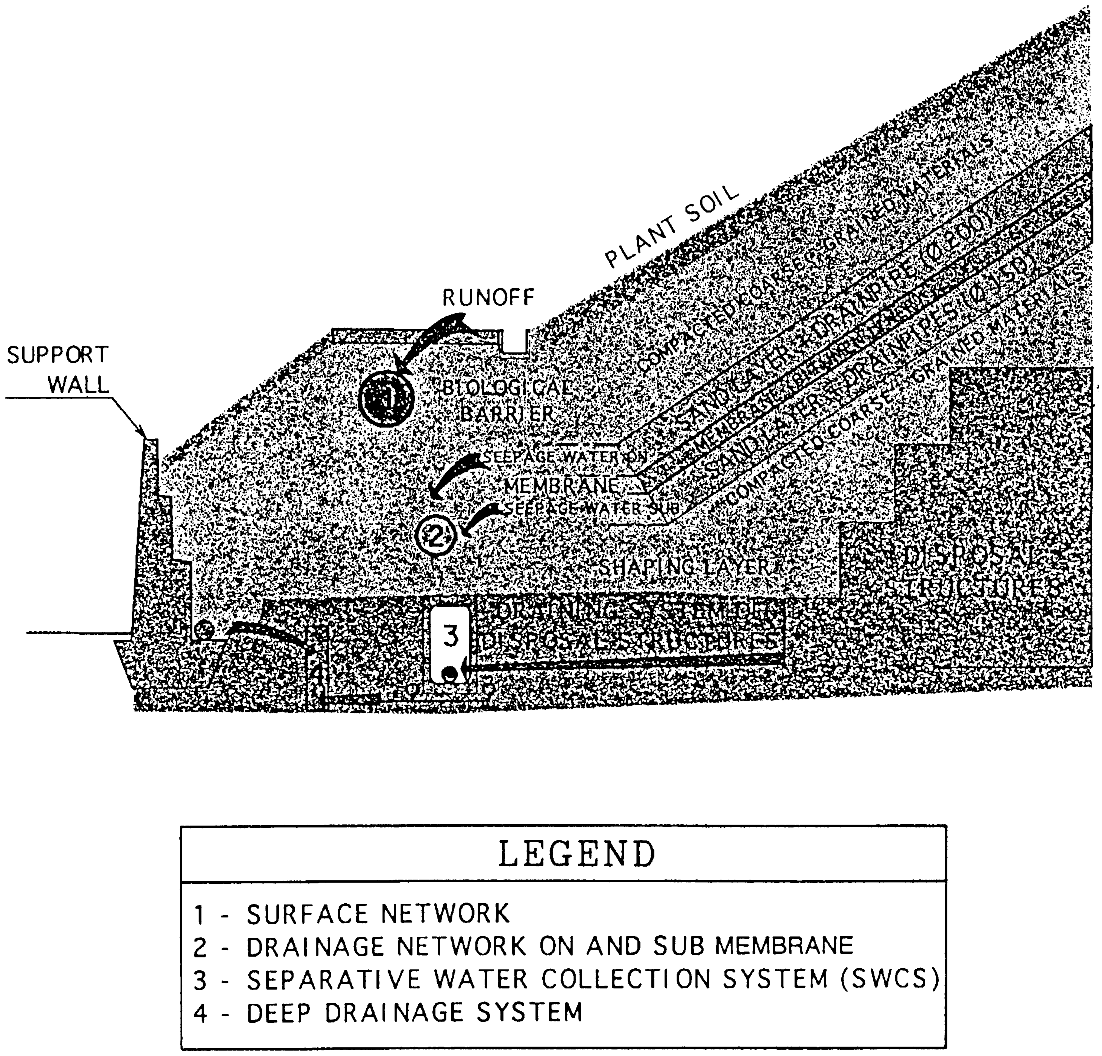


FIG. A.2. Cross section of the cap covering on Centre der la Manche.

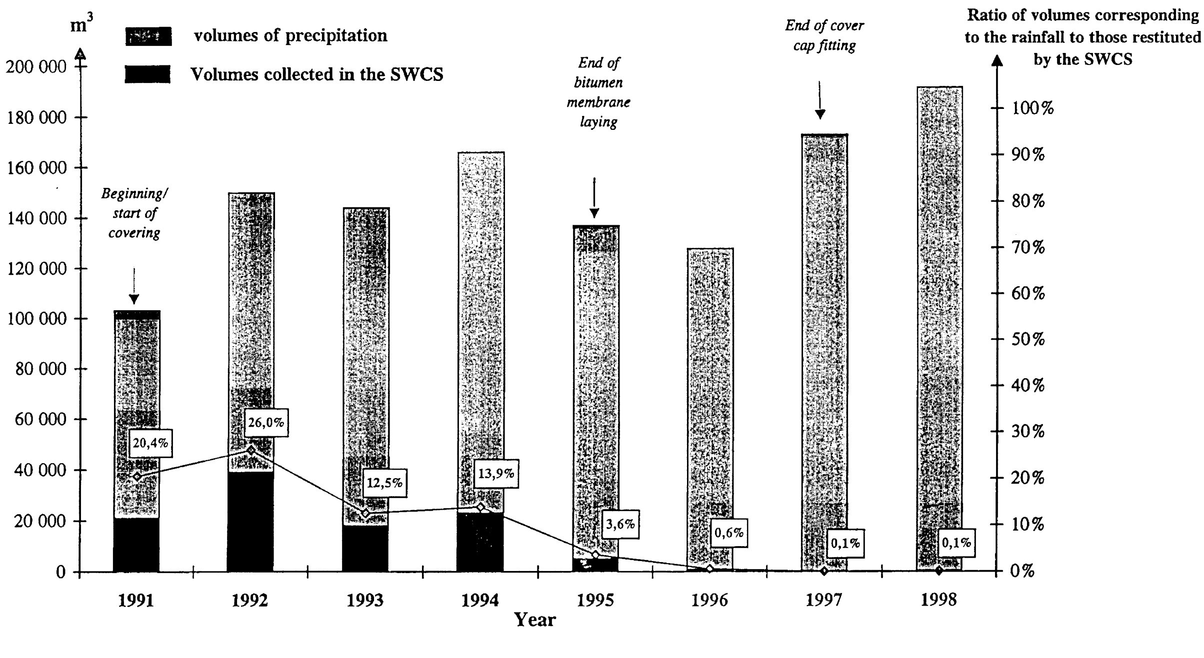


FIG. A.3. Precipitation and percolation data for the Centre de la Manche cover.

HUNGARY

CLOSURE ISSUES FOR CENTRALIZED WASTE TREATMENT AND DISPOSAL FACILITY IN PUSPOKSZILAGY HUNGARY

1. Background information

The facility was commissioned in 1976. At the time that its mission was formulated, the facility was designed to collect, transport, treat as necessary and dispose all radioactive waste originating from institutional use of radioactivity. The facility is government owned and presently operated by the Budapest branch of the State Public Health and Medical Officer Services.

The disposal site is located on the ridge of a hill near Puspokszilagy village approximately 40 km Northeast of Budapest. The disposal units are located in Quaternary layers of silt and clay sequences. Annual average precipitation is approximately 650–700 mm. The facility is a typical shallow land, near surface engineered type disposal unit. There are concrete trenches and shallow wells for waste disposal purposes. The disposal units are categorized into 4 classes, as abbreviated by letters:

- the "A" type disposal system consists of the original 48 vaults, 70 m^3 each and the extension built during the end of the 1980's: 6 vaults, 140 m^3 each plus 12 vaults with 70 m^3 volume;
- the "B" type disposal system consists of 16 wells with diameter of 40 mm and 16 wells with diameter of 100 mm. The wells are stainless steel lined and 6 m long, located inside a concrete monolith structure;
- the "C" type disposal system consists of 8 vaults, 1.5 m^3 each proposed and used for organic solvent disposal;
- the "D" type disposal system consists of 4 wells with diameter of 200 mm. The wells are stainless steel lined and 6 m long.

Up to now about 4800 m^3 of solid and solidified waste has been emplaced, with 2300 m^3 of that volume originating from the Paks NPP. The licence of the facility is valid for Low and Intermediate Level Wastes. From the NPP, only solid, compacted trash wastes were transported to the facility. According to facility records the total activity in the wastes emplaced in the facility is about 400 TBq.

Neither the original licence nor the licensing of the extension deal with waste acceptance criteria. It was the obligation of the facility to take all radioactive waste generated by isotope applications.

2. Waste classification and safety issues

The Hungarian Standard MSZ 14344/1 is the only guidance on waste classification. According to the standard the following categories exist:

- low level waste,
- intermediate level waste,
- high level waste.

In the 1989 edition of the Standard, distinction has been made with respect to the lifetime of the radionuclides in the wastes:

– short lifetime — less than 30 days half-life
– medium term lifetime — less than 30 years half-life
– long lifetime — more than 30 years half-life

In the earlier version of the classification standard, no distinction was made on the basis of the half-life. Following adoption of the 1989 edition, no changes were made in the licence conditions of the facility neither with respect to activity concentration nor restricting the long lived components for disposal.

Since the beginning of operation in 1976 till the end of 1996 the following activity has been disposed:

Isotope	Half life [yr]	Cummulative activity [GBq]
Co-60	5	106725.0
H-3	12	214937.0
Sr-90	28	41073.0
Cs-137	30	7391.2
Pu-238	88	414.2
Am-241	458	1391.0
Ra-226	1622	64.5
C-14	5568	1765.5
Pu-239	24000	1398.9

Note: These figures include estimated amount recovered from the earlier used Solymar storage facility.

A human exposure scenario has been analysed to calculate dose consequences and the obtained dose values had been compared against the dose limit (250 μSv/yr in the written legislation and 100 μSv/yr as a goal).

As an illustration the table below summarize the dose consequences for the existing waste in the disposal facility using conservative radionuclide migration rates:

Isotope	Dose from drinking water [μSv/yr]	
	Effective ESF	w/o ESF
H-3	0.835	0.0
C-14	0.094	1.86
Sr-90	0.0	0.0
Tc-99	0.001	0.03
Ra-226	1.84	9.20
Pu-239	0.016	32.5

3. Present operational practices

Emplacement of waste packages into A type vaults has been followed by backfilling the void places with cement grout prepared by very low activity liquid wastes. This was applied to originally built A type vaults. Presently all wastes are conditioned and packed into drums and backfill material for the extension has been changed to silty-clay containing fine sand.

After filling up a single vault, isolation from the ground surface is completed by the following way:

- 15 cm thick inactive concrete covers the waste packages,
- 19 cm thick prefabricated reinforced concrete panels are placed on the top of the vault,
- gently sloping (appr. 1 %) cementitious mortar layer of 5–10 cm is created,
- water isolation containing 0.5 cm bitumen layer, bitumen impregnated textile and 1 cm thick sand layer is created,
- 6 cm thick concrete protects the water isolation,
- temporary clay cap of 1 m thickness covers the isolated vault, with an additional 15 cm thick topsoil for grass.

First failure of the water isolation is expected after 12–15 years, while the lifetime is being assumed to be 30–50 years. The temporary caps thickness has been derived from dose limit of 1 mSv/yr. Requirement on clay is 10^{-6} cm/s hydraulic conductivity and 85–90% theoretical density. Temporary cap is used while filling of the vaults is completed.

4. Regulatory requirements and conceptual planning of closure

There is an existing requirement to have at least 50 years of active institutional control period after the site closure. This is not a fixed term, because the authorities shall decide after this period on the further length of active institutional control. During this period the surface water drainage systems, fences and basic characteristics of the cap have to be maintained, there is a need to prevent biointrusion and repair any damage (subsidence, ponding, holes) to the cap.

Closure of the facility (Figure A.4) will include construction of a final cap of a few meters thickness including drainage layers and biointrusion barriers. Slope of the final cap has been calculated on the basis of mat sliding in the event of an earthquake of MCS intensity 7–8 balls. In which case, the slope cannot be higher than 8^{o} while the top part should have slope 2–3^{o}.

There are two important socioeconomic issues affecting repository closure: one is the need for green field shut down (at least for cost calculation purposes) and the consideration of retrievability during the operational phase of the repository.

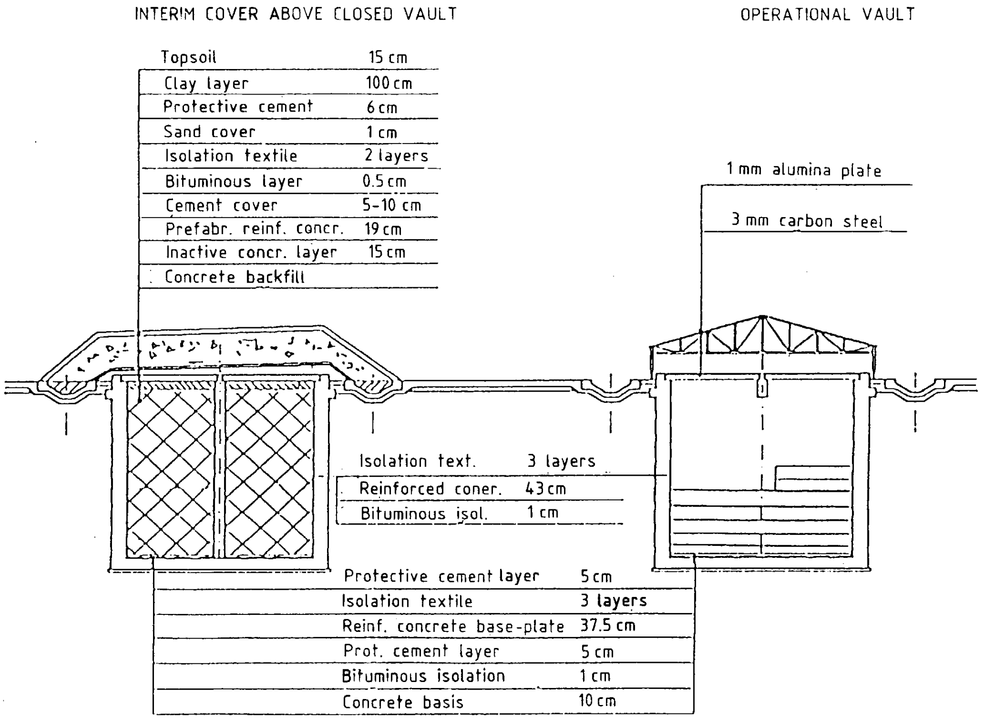


FIG. A.4 Cross section of "A" type vaults of the Püspökszilágy disposal facility.

INDIA

In India, each nuclear reactor site has been provided near surface repositories for low and intermediate level solidified radioactive waste. It is a policy decision to provide such repositories in view of the logistics involved in the transportation of radioactive waste across long distances. Based on the experience gained, the concept of design and development of shallow ground repositories has undergone a steady evolution. Some of the major factors which differentiate current approach from the initial stages relate to, establishment of an adequate buffer zone, between the operational areas and external boundary of the repository, clear isolation of administrative and support facilities from the operational area, provision of areas and equipment for the purpose of decontamination, extensive use of mechanised handling and number of post operational monitoring and other institutional controls for routine surveillance of the facilities.

The pilot Near Surface Disposal Facility (NSD) operated during 1958–1962 is the only surface repository that is non-operational. Near Surface Disposal Facilities currently under operation in India, are:

- NSD at Trombay, Maharashtra, operational since 1962,
- NSD at Tarapur, Maharashtra, operational since 1968,
- NSD at Kota, Rajasthan, operational since 1972,
- NSD at Kalpakkam, Tamil Nadu, operational since 1974,
- NSD at Narora, Uttar Pradesh, operational since 1990,
- NSD at Kakrapar, Gujrat, operational since 1994.

These repositories are integral part of power station complex within the exclusion zone of 1.6 km radius from the reactor building. All these NSD facilities have a multiple barrier approach viz., the waste matrix, engineered barriers and host geology of the disposal site. These facilities have multiple disposal cells involving earth trenches, reinforced cement concrete trenches/vaults, steel lined concrete tile holes and high integrity containers.

Each NSD is sub-divided into zones to plan various types of disposal systems. All the zones are served by a network of roads having sufficient width and turning radius for heavy equipment. Proper attention is given for drainage of surface water. A buffer zone is kept between disposal facilities and repository boundary to delay the migration of radionuclides.

Water tightness of all these concrete structures is ascertained. An additional layer of water proofing membrane is provided to protect concrete structures from chemical attack, in addition to serving as an impervious barrier. Reinforcement steel used is of high yield strength deformed bars. The concrete is designed to water-holding concrete structure specifications of M-20 or richer grades. Sulphate-resistant, low tricalcium aluminate cement, non-reactive aggregates and inert fillers, like garnet and granite sand, are used with regard to sealing of trenches and tile holes. These are designed to facilitate placement of precast concrete slabs on the top, after the trenches/tile holes are filled, to provide necessary shielding. Over the precast slabs, a reinforced cement concrete (RCC) upper cover is provided with properly spaced construction joint. Necessary slope is given to the upper cover to facilitate self-drainage. The top cover is further waterproofed with multiple felt bitumen coating, and sealing the overlapped joints and open ends. To provide necessary biological shielding and working space around the disposal facilities, earthen embankments with stone pitching are provided on all sides of the facilities. The slopes of the embankment are in accordance with the angle of repose of the soil.

Models have been developed to assess and predict long term performance of engineered barriers and also migration of radionuclides from NSDs for each site. These incorporate soil characteristics and surrounding hydrology of specific sites. These models are validated based on the data collected from borehole monitoring and other periodic sampling.

Surveillance has been provided at all NSD facilities. A grid of boreholes is provided in the direction of ground water movement near to disposal facilities and at the boundary of the site. Samples from boreholes near trenches and tile holes are regularly monitored. Periodic investigation of soil and vegetation samples are also done to check for any uptake of active contamination. Trenches have been provided with inspection pipes to monitor the condition inside after closure and facilitate checking of any ingress of water in wide space and subsequent removal, if required. Independent radiation surveys by environmental groups is part of the approved procedure to monitor for radioactivity on top of the closed disposal facility and at the perimeter fence.

REPUBLIC OF KOREA

CLOSURE CONCEPT DEVELOPMENT FOR LILW DISPOSAL FACILITY IN REPUBLIC OF KOREA

1. Background

Nuclear Environment Technology Institute (NETEC) of Korea Electric Power Corporation (KEPCO) is developing near surface disposal concepts for both a rock cavern type disposal facility, and a vault type facility; two types of facility are being considered to provide more options for LILW repository siting. The conceptual design for the vault type facility will be completed in 1999. As a part of conceptual design effort, a preliminary concept for the disposal facility closure has been identified.

2. Laws and regulations for the disposal facility closure

The basis for disposal facility closure was provided in several notices of Ministry of Science and Technology (MOST) as follows:

- MOST Notice No. 91-9
  - (Art. 16) Closure time
  - (Art. 17) Environmental monitoring during post-closure
- MOST Notice No. 94-4
  - (Art. 4-4) Site surveillance and investigation plan followed by site characterization
- MOST Notice No. 96-11
  - (Art. 8) Establishment of institutional control period to ensure maintenance and surveillance activity
  - (Art. 15) ALARA concept and minimization of radiation exposure during both operational period and post-closure period

However, a regulation devoted to the LILW disposal facility closure is not finalized yet. Nonetheless, a draft of the regulation is already available and the regulation will be used during the designing and licensing stage of the repository project.

3. Regulatory requirements for closure

- General guideline
  - * Closure plan should be prepared for temporary closure and final closure of the repository site, respectively.
  - * A separate plan for normal closure and accidental closure should be considered.
- Contents of application for closure
  - * Prior to final closure of the disposal site, a final revision of the safety analysis report should be prepared.
  - * Final cover, backfill and sealing should show impermeability, long term containment of disposed waste, minimum repairing requirement, and resistance to intruders.

– A responsible organization should be specified for maintenance of records.
– Post-closure environmental monitoring, maintenance and access control.
  * Post-closure environmental monitoring plan should be approved as a part of the site closure application.
  * An organization responsible for post-closure monitoring, maintenance and access control should be specified for active institutional control.

4. Closure system being considered in the near surface disposal facility design

– Probable site conditions
  * The repository site will be selected in a coastal area.
  * After exclusion of densely populated area, level plain, and reclaimed land in coastal area, a hilly terrain is likely to be selected.
  * Average rainfall is around 1300 mm/yr and maximum rainfall intensity is around 150 mm/hr in rainy season from June to August.

– Disposal structure and closure system design
  * Concrete vault type will be chosen.
  * Closure system will consist of multi-layers utilizing mainly soil borrowed near the repository site.
  * Landscaping and earth moving to secure enough space in consideration of final cap installation around the array of vaults.
  * At the early stage of disposal operation, a few prototypes of full size cap system will be constructed for in situ physical testing and monitoring before the final selection of a cap design for implementation.
  * Considering rainfall condition of this country, fast drainage is essential, and a separate drainage for the final cap will be added for the drainage over the cap.
  * Freeze-thaw depth of approximately 1 meter will be considered in the cap design for the freezing season from November to February.

RUSSIAN FEDERATION

1. Introduction

In the Russian Federation (RF), management of radioactive wastes will be carried out within the framework of the Federal Target Program for management of radioactive wastes and used nuclear materials for the period 1996–2005. The agency within the RF responsible for this program is the Ministry of Russian Federation on Atomic Energy.

Current radioactive waste disposal activities are focused on creating regional repositories for wastes generated by radiochemical production, nuclear reactors, science centers, and from other sources outside of the nuclear-fuel cycle (the latter wastes are managed by Scientific and Industrial Association, "RADON"). Wastes of these types are in temporary storage, with the exception of non-fuel cycle wastes which are in long term storage managed by SAI "RADON". The criteria for segregating between underground or near-surface disposal of radioactive waste are based on the radiation fields and radionuclide composition of the wastes.

The most progress in creating regional repositories has been made in the Northwest region of Russia. However, development of a detailed design has begun for a test facility in the Northeast for disposal of radioactive wastes generated in Murmansk and Arkhangelsk provinces. The feasibility study for construction of this facility is being evaluated by state monitoring organizations, the heads of administrations of the Arkhangelsk and Murmansk provinces, and Minatom of Russia.

2. Nuclear fuel cycle wastes

The candidate site for the test facility is located on the Southern island of the Novaja Zemlja archipelago in region of Bashmachnaja gulf. Rock outcrop indicates that the surface soils at the site are mainly strong chalkstones. From a geocryological point of view, the region is characterized by:

- presence of merged permafrost of continuous propagation by depth up to 300 m,
- depth of seasonal thawing from 0.5 up to 2.0 m,
- free water in rock that is completely frozen.

Under these conditions, radionuclide migration rates are very slow.

The sequence of activities anticipated for the repository include the following:

- drilling, blasting, and excavation work for the trench,
- trench construction,
- emplacement of radwaste into the trench,
- construction of engineered barriers above the waste, and
- construction of facility cover using soil excavated at the site.

The waste to be placed in the facility is compacted, stacked and surrounded by a cement backfill which has a low permeability when hardened. The cemented radwastes are to be covered with soil that was excavated during trench construction. The volume of soil used for filling and covering the trench will be about 75 % of volume generated during excavation.

Practices which are used to ensure the long term integrity of the facility include:

- backfilling with layers of fine-grained and large-sized rocks, and
- installing of thermosiphons to remove heat from the repository.

Isolation of the waste is achieved by allowing permafrost to reestablish within and around the buried waste (see Figure A.5). The baseline surface of permafrost is much below the bottom of repository. Therefore reestablishing the permafrost within the waste burial zone is assured. The sidewalls of the repository are located below the zone of seasonal thawing so that horizontal migration of radionuclides is also minimized.

The soil cover over the repository is to be 5–7 m thick. Porosity in the cover soil will be 10–20%; some settling and liquid from melted snow and ice may permeate to these void spaces. However, the cement backfill between and above the waste packages will prevent access of infiltration to the wastes. Some water is expected in the waste just after backfilling operations are completed. However, after the first winter season, permafrost reestablishment will begin and after 1–2 years will lock up any water present in the waste environment. The time of complete freezing of the waste environment is 1–2 years with the thermosiphons in place and 10–15 years without them.

Thus, the long term isolation of the waste relies on the reestablishment of the permafrost; in the short term, the waste packaging and cement backfill surrounding the waste prevent waste migration until the permafrost is reestablished.

3. Non-fuel cycle wastes

3.1 Existing repository

As mentioned above, SAI "Radon" (established in 1961) is responsible for managing all LILW generated outside of the nuclear fuel cycle in the central part of the Russian Federation.

The population of this region of RF is about 40 million people. The number of facilities that generate radioactive waste in the central part of the Russian Federation (waste generators) is about 2,500. Among those waste generators are industrial enterprises, educational institutions, medical and research institutions, and military installations. The waste arisings from environmental and facilities rehabilitation has increased in recent years.

More than 30 repositories are now used for the disposal of radioactive waste by SIA "Radon". Disposal of the LILW is carried out on the disposal site of the Sergiev Posad (Zagorsk) division of SIA "Radon". Near surface reinforced concrete repositories are used for this purpose. The bottom and walls of these repositories are lined with waterproofing materials. Most of these repositories are excavated into the soil although some have both above-grade and subsurface disposal cells. Typical dimensions of the repositories are 60 m long, 20 m wide and 4 m deep. The waste forms in various packages are emplaced into the repository in layers. Every other layer, with the thickness about 1.5 m, is poured by cement mortar.

The immobilization of radioactive waste is achieved by applying the multi-barrier principle. The repository barriers include the repository walls and natural soils surrounding the repository. Protection against radionuclide migration is also provided by the waste matrix materials (concrete, glass, bitumen, metal), the package (concrete or steel container, metal drum, lead container) and, stabilizing backfill materials (cement mortar, cement-clay mortar, natural sorbents).

The final status of the facilities at Sergiev Posad — whether they are “storage” or “final repository” — has yet to be determined. A resolution cannot be approved at state level under the prevailing social-political framework, and legislation and regulatory documents concerning long term closure and institutional control activities for radioactive waste repositories have yet to be promulgated.

3.2 New repository design

The basic design of a repository for conditioned forms of radioactive waste was prepared recently within the framework of the TACIS Program (see Figure A.6). Requirements, as stipulated by the Consortium “Belgatom-SGN-AEA Technology, are that for the first 50 years, the waste must be stored in a form that is retrievable. During this time period, an interim cover will be used consisting of a reinforced concrete slabs with 0.4 m thickness and a waterproof covering. After the end of this period, when a decision will be made on the disposal status, a final cover will be built, which will have the thickness in the central part about 4.5 m (Figure A.6). The sealing cover will be comprised of 11 layers including vegetative cover, coarse materials, clay, a geomembrane, silt, sand, monolith concrete with the thickness 0.7 m. These materials are layered to provide:

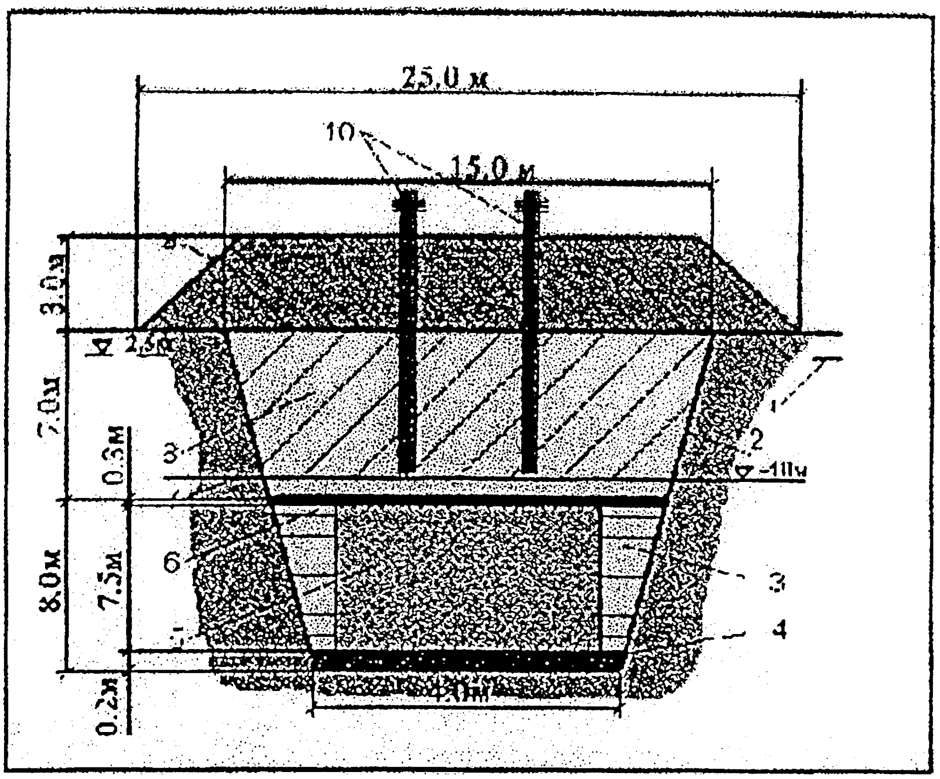
- protection against infiltrating water,
- erosion protection,
- protection against excessive penetration of plants roots (i.e., biointrusion),
- prevention of drying and cracking of waterproof layers,
- prevention of intrusion by burrowing animals,
- freeze-thaw cycling,
- measures to prevent slip between separate layers,
- drainage of rainwater and snowmelt.

The cover overlaps the sidewalls and extends from 10 to 15 m depending on the slope. The side shields are comprised of sand, clay and large-sized material.

An advantage of this design is the possibility to fill the repository from lateral openings with the concrete covering already in place. A further advantage is that the facility is protected from infiltration and surface water during the operating phase, and it offers the possibility of corrective actions, if any are needed.

Inspection drainage galleries supply construction (repository). They are designed for control and removal of leaks both for operational and institutional control periods. A peripheral circular channel is constructed for removal of surface water flow.

The newly designed facilities are currently classified as storage, but can be transformed into a final repository. Corresponding decisions on this transformation will be taken during the following 50 years.



1. boundary of a layer of seasonal thawing
2. sinken trench
3. working volume of repository
4. concrete foundation
5. containers
6. engineering barrier
7. high bound of soils with zero amplitudes of oscillatings of below zero temperatures
8. filling of trench by a ground
9. technological balk of soils above trench
10. seasonal cooling unit.

FIG. A.5. Disposal of radioactive waste in permafrost rock trenches (Russian Federation).

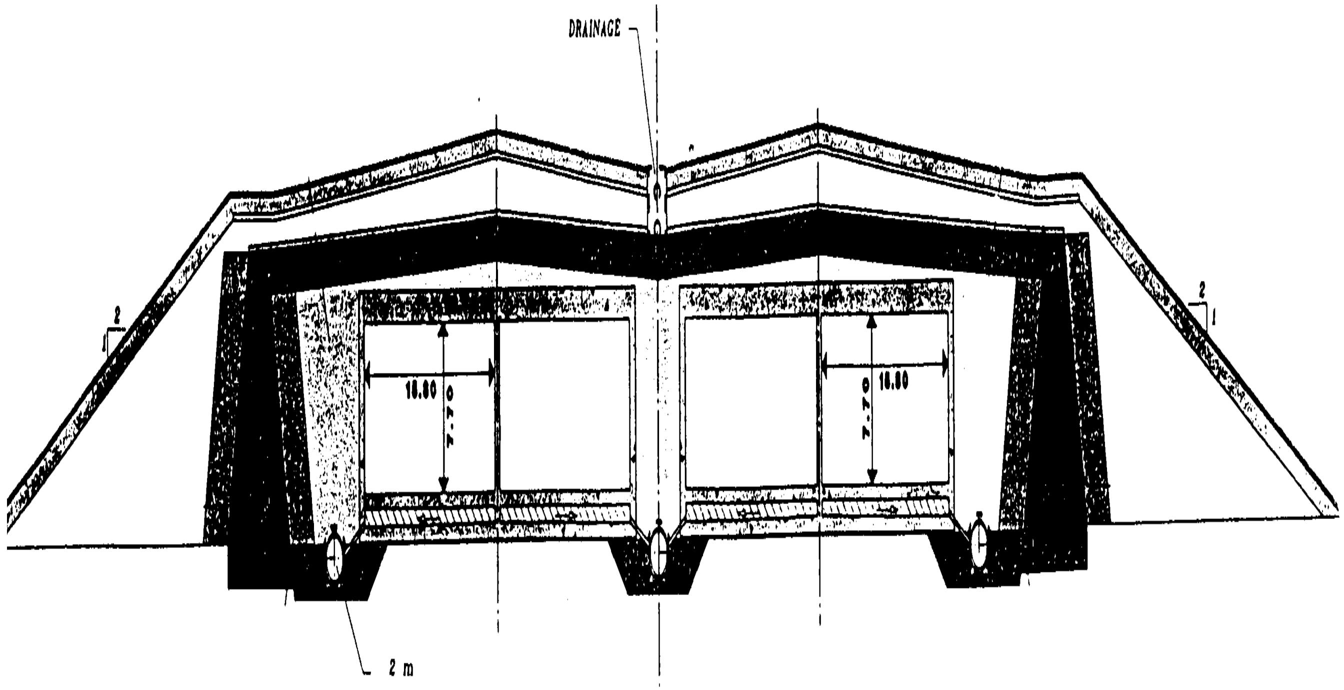


FIG. A.6. Basic design of new repository for conditioned radioactive waste.

SOUTH AFRICA

CLOSURE PLAN OF AN OPERATION AT LILW REPOSITORY IN SOUTH AFRICA

1. Background

Vaalputs, the South African, National Radioactive Waste Management Facility, is situated in an area of the Northern Cape Province and is operated by the Atomic Energy Corporation of South Africa Limited. Screening and site selection lasted from 1978–1984, construction took place from 1984 to 1986.

The waste received is predominantly from the Koeberg nuclear power station and low and intermediate-level radioactive waste is disposed of in a near surface disposal facility in clay. Two trenches were excavated for use, one is used for concrete containers and one for other waste, mostly compressed trash in 200-liter drums. No capping of trenches has taken place as it was originally anticipated that the trenches would be capped after being filled. Much slower delivery of waste packages and other problems has led to a process of temporary capping.

2. Regulating requirements

There are no formal regulatory requirements specifying the cap design, however, it is required that overall cap requirements will minimize risk to humans and the environment from the repository and will maintain its integrity during all possible anticipated weather conditions during the periods of operation and institutional control.

3. Systems

3.1 Site

The screening phase commenced in 1979 on a national basis and included the parameters, i.e. climate and rainfall, agricultural density, population density, ecologically sensitive areas, mineral occurrences, surface and ground water, seismic hazards, industrial ground potential and proximity to international boundaries. A few sites were identified and the site-selection phase which involved regional and semi-regional geological, geohydrological, geophysical and other earth science related studies. A site was selected where there was an area underlain by approximately 20 m of clay. The area is covered by a veneer of calcrete and windblown sand and overlies a granite-gneiss suite.

3.2 Design

Two trenches 100 m × 20 m × 7.5 m deep were constructed. One trench was to be used for concrete containers (Figure A.7) and the other for metal drums. The clay layer is very stable and the walls of the trenches were constructed at an angle of 10^o from the vertical. The cap for the trenches would be constructed from the same clay and sand material that was removed from the trench. Different layers of the soil were kept separate during the excavation phase. Screened clay with a moisture content approximately 5% is used for backfilling between the containers.

The top 2–3 meters of the trench consists of the trench cap (Figure A.8). The screened clay will be compacted in layers 150 mm thick and will have a slight slope from the center of the trench to the sides. Compaction, permeability, moisture storage capacity, shrinkage and elasticity laboratory tests were performed. The moisture content of clay for the compaction process was found to be ± 13 %. This value is just on the dry side of optimum for compaction purposes, to provide increased water storage capacity. The water in the clay will then be available for evapotranspiration. The original sand will be placed over the compacted clay to a minimum of 300 mm. Vegetation from the area will be replanted on the trench and it is anticipated that micro irrigation will be used till the vegetation is established after which the irrigation will be discontinued. Vegetation in this area is mostly small bushes, while grass is almost non-existent.

3.3. Performance assessment

Water storage capacity tests and calculations showed that 300 to 400 mm of rainfall, which is 4 to 5 times the annual rainfall for the area, could be absorbed by the cap. Experimental caps that were constructed for performance assessment satisfactorily prevented rainwater infiltration into the trench during a 1 in 100 year rainfall event that occurred during December 1985.

Delivery of waste was much slower than originally anticipated and some concrete containers developed cracks and some metal drums corroded. It was believed that both of these effects were due to the waste packages being exposed to the elements for much longer than anticipated. When waste packages are in place, a wall of concrete blocks was built across each trench. It is intended to construct a cap over the packages and up against the wall. Concrete blocks were also used to construct small disposal modules.

The smaller compartments in the trench will be temporarily covered. These temporary caps will be 0.3 to 0.5 meters thick consisting of a 150 mm sandy clay layer on top of the waste packages, followed by a 1 or 1.5 mm geomembrane, and a clay cap on top of that of approximately 200 mm. The geomembrane will overlap the concrete wall and joint welded on to the next compartments geomembrane.

3.4. Site intrusion

Human intrusion

Due to poor natural resources, the acid climate and prolonged low population density, the site is of low growth potential. Human intrusion is therefore not considered as of any significance.

Animal intrusion

Various burrowing species occur on the site or its vicinity and are being decided as part of an on-going programme to investigate possible disturbing agents. The common harvester termite poses the greatest potential impact on the disposal trenches. It has the ability to excavate to depths in excess of 9 m, which is below the trench floor. Due to the plugging effect of soil slurry, water will not penetrate the termite burrow. The possibility exists that radioactive contaminants on sand particles could be brought to the surface by the termites. The termite activity is most severe in denuded areas typical of the trench cap and it could adversely affect the revegetation programme as their diet consists primarily of dry grass. Experimented revegetation work on the caps of the experimental trenches has proved successful and the results of these studies will be applied to the actual trench caps. Any effects due to burrowing agents are expected to be slow and to occur in the medium to long term. The situation is monitored on an on-going basis and, if necessary, the activities of any burrowers will be curtailed by conventional means.

4. Procedures

The excavated soil from the trench is dumped in 3 different areas, sandy topsoil, calcrete and clay. The calcrete is screened and used on the bottom of a trench for a drainage layer. The clay will be screened and then spread out over an area about 150–200 mm deep, wetted and mixed by mechanical equipment. Clay with the dried moisture content is placed over the containers in the trench, levelled and compacted. It is anticipated that a compaction density of 1, 700 to 1, 800 kg/m^3 will give a permeability in the order of 1×10^{-5} cm/s.

5. Technologies involved

The waste repository is in an arid area, therefore, the cap design employs the resistive barrier concept of a low permeability layer, as well as a vegetation cap to protect the cap against erosion. The vegetation cap is also plays an important roll in removal of soil moisture by transpiration.

6. Quality assurance

A quality assurance program to ascertain that design specifications are met and that construction work is done according to approved procedures will be in place before the construction of the cap starts.

7. General

7.1. Public acceptance

The policy of the AEC is to keep the public involved in all of its activities as far as possible. There are a number of public organizations, selected by the community, that meet regularly with the AEC to give feedback to their constituents on AEC activities. They are: (1) The Pelindaba Communication Forum; (2) Vaalberg Trust; (3) Local Farming Association in Springbok (near Vaalputs); and (4) Local Fence Committee (Vaalputs area).

7.2. Cost

Estimated cost of capping the Vaalputs trenches with clay layers and sand topsoil is approximately \$ 50 /m^3 (U.S.). Introducing a geomembrane will increase the cost with \$ 10/m^3.

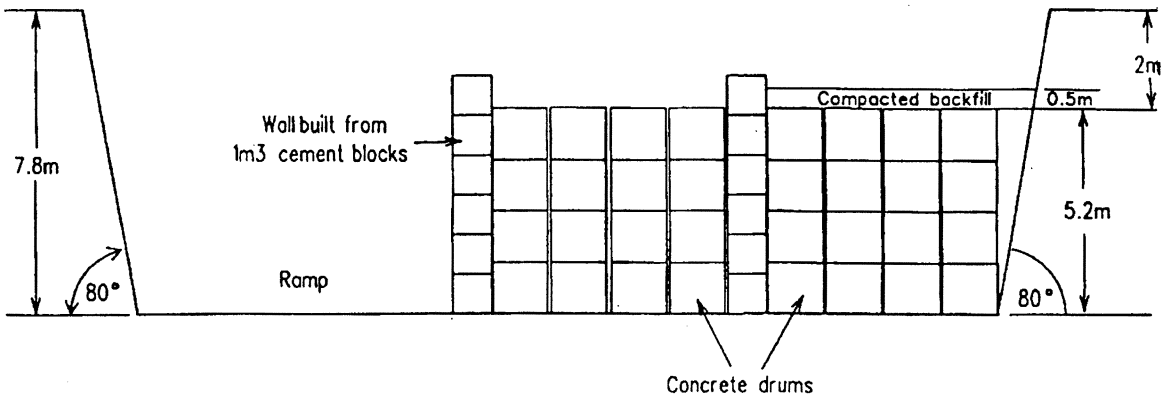


FIG. A.7. Cross-section through proposed disposal modules (South Africa).

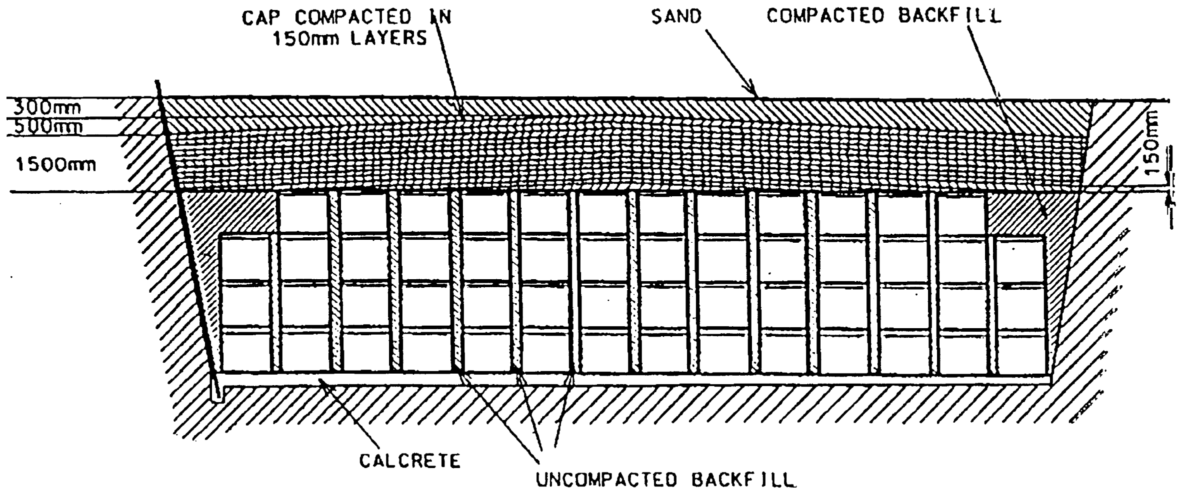


FIG. A.8. Detail of backfilling and cap construction (South Africa).

SPAIN

1. Introduction

Spanish low and intermediate level radioactive wastes are disposed of at the El Cabril Disposal Facility, in the province of Córdoba (SPAIN).

The fundamental safety objective of the facility consists of the immediate and longer term protection of people and the environment. This objective leads to the need to isolate the wastes from the human surroundings, such that any release of the radionuclides contained in them does not pose any radiological risk for either people or the environment over the necessary time period.

Consequently, it is necessary to fully protect the wastes against external aggression, from both the climatic and biological point of view (infiltration of water, temperature variations, chemical action of water, attacks by living macro and microorganisms, plants, etc.). This waste isolation is achieved by means of a multi-barrier system separating the activity stored from the aforementioned actions. The system is made up of the following barriers:

- The first is formed by the immobilizing matrix of the wastes themselves and by an isolating storage container.

- The second consists of the bottom of the structures housing the containers, a low permeability cover which is placed over the structures following their closure and a seepage control network. This second barrier limits the access of water to the waste packages and makes it possible to control whatever water might have come into contact with them, including subsequent treatment if necessary.

- The third or geological barrier is made up of the surrounding terrain. This barrier would limit the impact of any eventual leaching in the event of an accident or in the hypothetical case of complete degradation of the first two, adopted for the phase subsequent to the foreseen duration of these barriers.

- Finally, a final cover will be installed, made up of a series of layers isolating the storage structure from the biosphere. This cover is required to maintain its characteristics throughout the lifetime of the facility.

  The functions to be provided by the final cover are as follows:

- Impermeability to infiltration,
- Protection of the subsurface barriers.

2. General requirements

The requirements applied by the Spanish Regulatory Authority include the need to draw up a closure plan, which must contain all the aspects of relevance for evaluation. A generic list of the relevant factors would include:

– final inventory of waste and radioactivity emplaced,
– design of definitive cover,
– radiological impact of closure,
– safety or performance analysis,
– surveillance of seepage and groundwater,
– quality assurance, including real operational and construction records.

Many of these aspects have already been quantified in order to obtain the operating permit for the facility. It is of paramount importance to have a good tracking of the emplaced activity to support the detailed safety analysis for the closure. A closure Final Safety Analysis report is considered as important in support of the closure and surveillance operations. A radiological dose limit should be defined for the surveillance and post-surveillance period. In Spain a limit of 0.1 mSv/yr (risk of 10^{-6}) has been defined by the Nuclear Safety Council.

3. Definition of surveillance concept

Considerations are given to establish a surveillance concept for the repository post-closure period. Included in the considerations are:

– marking,
– records,
– definition of surveillance responsibilities,
– cost of surveillance,
– funds management,
– length of surveillance period as a consequence of emplaced radionuclide inventory,
– risk limits,
– safety assessment,
– minimization of maintenance,
– security (if required),
– files requirement,
– intervention in case of necessity.

4. Conceptual design of final cover

In view of the fact that the fundamental function of the cover is to protect the storage structures against the infiltration of rainwater, erosion by external agents, both physical and biological, and, ultimately, protect mankind and the environment from possible leaks. To meet the aforementioned requirements, the closure system designed will consist of the following series of layers (Figure A.9):

– backfill made up of duly compacted excavated material which is in contact with the storage structure,
– a layer of sand, designed to provide drainage,
– bituminous membrane which acts as the first impermeable barrier,
– a layer of sand serving as a filter,
– a layer of compacted clay,
– a layer of sand for further filtration,

– a layer of coarse gravel, over which is placed a layer of soil (The gravel and soil make up the biointrusive barrier, preventing animals and the roots of certain plants from penetrating the clay layer),
– a layer of soil in which are planted suitable plant species (rapid growth and shallow roots),
– a mixture of gravel and soil placed over the previous layer to prevent erosion, at both the top and the slopes.

Other conceptual designs cannot be excluded. At least one alternative option is under consideration: a synthetic membrane (polyethylene or bituminous) on a form layer of crushed rock from the area, with a drainage layer on it and protected by a thick crushed rock layer to provide protection and stability.

The design of the cap have to be consistent with safety assessment requirements as approved by the regulatory authority and other facility design. In this sense, and in the specific case of El Cabril, the cap has to consider the following parameters:

– infiltration rate to the cap (1.5 $l/m^2/yr$),
– specific weight of the cap (1.8 t/m^3),
– minimum thickness (2 m: derived of human intrusion events),
– duration of institutional control (300 years).

5. Design confirmation program

In order to confirm the suitability of the design of the final cover, it is necessary to develop and perform a research program making it possible to confirm all the parameters considered as being characteristic of the system.

The parameters to be analyzed as part of the aforementioned program would be as follows:

– differential settling,
– drying of the clay layer,
– erosion of the cover slopes,
– cover drainage,
– seepage.

6. Model for evaluating erosion events

Since 1990 ENRESA (Empresa Nacional de Residuos Radiactivos, S.A.) has been carrying out theoretical and experimental studies for the establishment of soil erosion rates in the area of El Cabril (Córdoba). The experiments are being carried out in both natural and anthropogenic areas with special attention to the taluses of the storage emplacement. The objectives of the experiments are to:

– evaluate spatial distribution of erosion rates in the area,
– calibrate a physically-based erosion model to provide a procedure for (a) evaluating soil loss in every event and (b) designing the final cover for the protection of the emplacement.

Initially the study was carried out applying the Universal Soil Loss Equation (USLE) with theoretical values for the parameters. However, difficulties calibrating the USLE with field data were encountered and it was decided to calibrate a physically-based erosion model, namely the European Soil Erosion Model, EUROSEM.

EUROSEM is a distributed event-based erosion model that, in addition to predicting total runoff and soil loss, produces hydrographs and sediment graphs. An experimental layout was designed, after a detailed inspection of study area, to collect data for EUROSEM calibration. The experimental sites were selected to be representatives of the 90–95% of the spatial variability in the area. The experimental layout consist in:

- 8 plots of 10 × 3 m in anthropogenic taluses,
- 2 plots of 20 × 3 m in areas with natural vegetation,
- 2 catchments.

Total runoff and sediment production from every event are collected in a tank at the base of the experimental sites. The size of the tanks were determined from plots or catchment size and expected runoff calculated from rainfall data and soil characteristics.

7. Spanish experience

The El Cabril low and intermediate level waste Disposal Facility is currently in operation, depletion of its storage capacity being foreseen for the year 2015. For this reason, the necessary site specific characterization work described is planned to start in the year 2002, beginning with the installation of the experimental caps. The main items to optimise are water infiltration and resistance to erosion as these are considered to be the major failure mechanism at El Cabril site.

ENRESA has already decommissioned the Andújar uranium mill, and a definitive cover made up of multiple layers has been constructed. The surveillance of the performance of this engineered cap is also considered as a part of the confirmation process for the cap technology used.

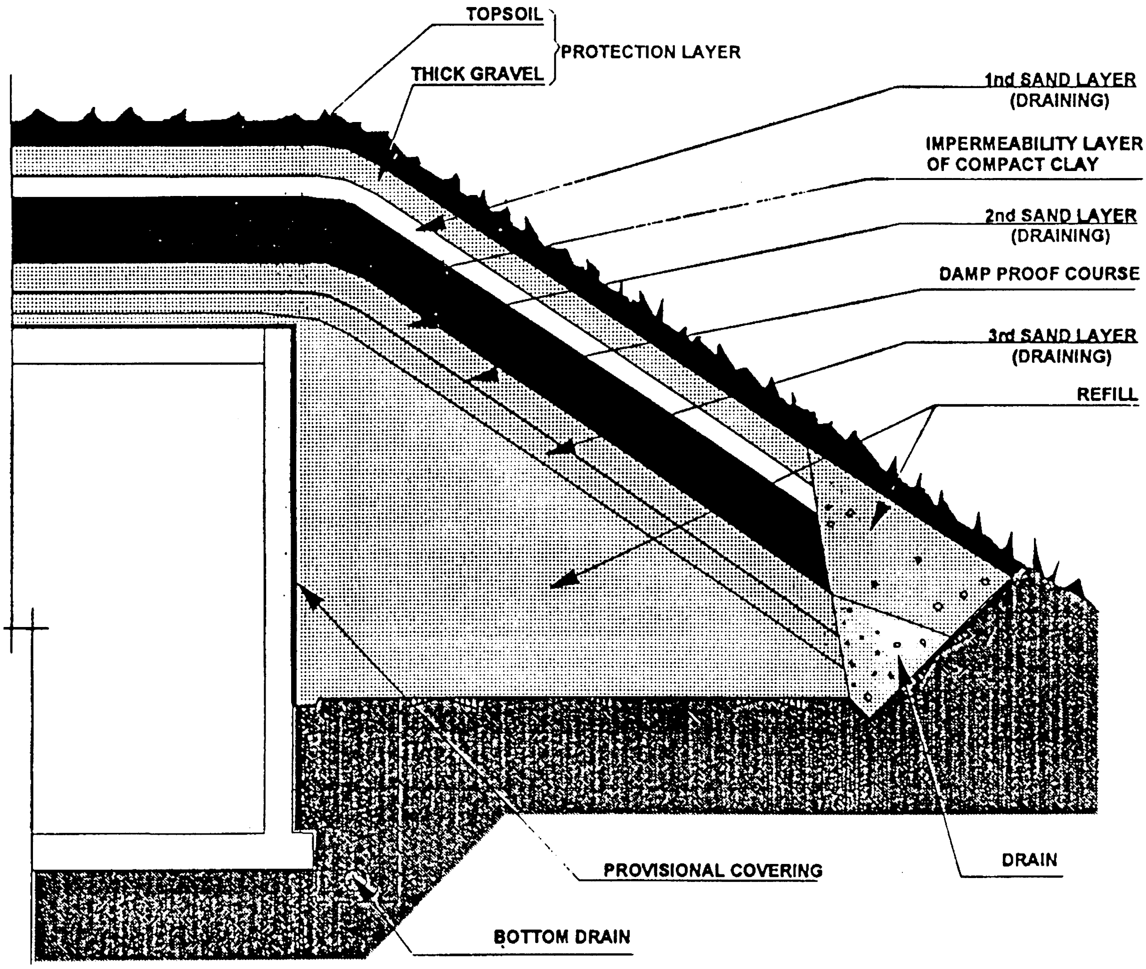


FIG. A.9. Concept of the final cover cap for El Cabril repository (Spain).

UNITED KINGDOM

DEVELOPMENT PLAN FOR THE EVENTUAL CLOSURE OF THE UK DRIGG NEAR SURFACE LOW LEVEL WASTE DISPOSAL FACILITY

1. Introduction

The Drigg site, owned and operated by BNFL, is the UK's principal site for the disposal of low level radioactive waste. The site has operated since 1959 and receives wastes from a wide range of sources including nuclear power stations, nuclear fuel cycle facilities, isotope manufacturing sites, universities, general industry and cleanup of historically contaminated sites.

Disposals until the late 1980s were solely by tipping essentially loose wastes into excavated trenches. More recently, trench disposals have been phased out in preference to emplacement of containerised, conditioned wastes in concrete vaults. The standardised wasteform consists of high force compacted (or non-compactable) waste immobilised within 20 m^3 steel overpack containers by the addition of cementitious grout. Larger items of wastes are grouted directly, in situ in the vault.

The disposal trenches have been completed with an interim cap, as will the vaults when filled. It is currently estimated that sufficient capacity remains at Drigg for disposals to continue until at least 2050. Post-operations it is planned that the site will enter a phase including shut down of operational facilities, emplacement of long term site closure features including a final closure cap and then to an institutional management phase. Planning has therefore been carried out as to the strategy for eventual closure of the site. This closure strategy is also underpinned by an engineering evaluation studies programme to develop and evaluate appropriate closure measures including assessment of the long term performance of such measures. This appendix summarizes some of this work.

2. Site closure plans

BNFL anticipate a series of phases relating to the control and management of the site:

- operational,
- post-operational management,
- institutional management,
- post-institutional management.

Planning by BNFL is on the basis that operational disposals are expected to continue until at least the middle of the next century. A further period of active management of the site for of the order of 100 years is planned. At the end of this phase, subject to a final assessment, the site would be closed as a disposal site and would potentially be available for other uses. At this stage the records would be transferred to the appropriate authority and a phase of institutional control would commence. This would incorporate planning controls to minimize the potential for human intrusion. As such controls cannot be guaranteed, in principle a final post-institutional management phase may also prevail in the longer term.

During the post-operational management phase the site would be maintained and appropriate facilities and environmental pathways monitored. Any remedial work would be carried out as necessary, for example to the interim cap in place over the trenches and vaults. During this period operational facilities would be progressively decommissioned and long term site closure features constructed. The detailed nature of these features will be developed with time in order to take into account good environmental and engineering practices and enabling future developments of relevance to be taken into account.

It is currently expected that specific engineering features will be provided during the post-operational management phase in order to augment the natural barriers provided by the site geology. The detailed nature of such provision is the subject of the ongoing scientific and technical studies. However, the features will take into account both the trenches and the vaults and act as an integrated system potentially composed of the following components:

- a multi-layer cap which includes vegetative cap, both human and animal/plant intrusion barriers and a number of infiltration barriers;

- a cut-off barrier surrounding the disposal area which will limit groundwater intrusion and lateral migration of leachate;

- an enhanced engineered drainage system within the disposal area to capture any ingress of water and to conduct any resulting leachate via a preferred pathway.

The overall aim of such a system is to minimize water ingress into the wastes, whilst maximizing dilution of residual contaminants released from the site before they impact upon the human environment. At the same time the system incorporates a number of features which are designed to minimize inadvertent human intrusion into the wastes and to allow gas release.

Of these three components identified above, it is fully expected that a cap broadly of the type described below will be installed as the primary component of site closure measures. The installation of the cut-off barrier and the enhanced engineered drainage system are at this stage more speculative pending engineering risk assessment work of their potential performance and evaluation of their radiological value in future optimization studies. For example it is not yet clear whether cut-off walls will decrease or increase the potential for bathtubbing, this being partly influenced by the performance of the cap and the timescales considered. For completeness however, all three concepts are described here.

2.1 Final cap

The purpose of installing the interim cap rather than immediate construction of the final cap is to allow time for the waste to settle under the influence of self weight and as a consequence of degradation. Only when the remaining settlement, as assessed by both the direct monitoring and from supporting considerations, is within the design specification of the final cap will construction proceed.

The potential total settlement in the trenches and vaults depends on a number of factors including waste degradation and the void volume associated with the waste. Current disposal practices restrict and minimize voidage in the wasteform disposed of within the vaults. This is achieved through good waste management practices during filling of disposal containers and by grout injection after the waste has been placed in the ISO containers to minimize residual voidage. It is currently planned that final capping of the vaults and trenches will proceed as a single project around 2100.

The principal functions of the final cap are to:

- maintain cap over the waste to minimize the effect of surface environmental processes (e.g. erosion, desiccation, freeze/thaw),
- deter intrusion by humans, animals and plant roots,
- minimize leachate volumes by controlling rainwater infiltration.

The cap must also allow degradation gas to vent to atmosphere in order to prevent pressure build up that may adversely affect the integrity of the overlying cap formation layers.

It is currently expected that the overall design will be a 1:40 graded earth mound overlying a 3 m thick sequence of specially selected engineering materials. The preliminary design for the basic structure of the cap incorporates the following:

- vegetated top soil to encourage runoff and evapotranspiration of rainfall. (The roots systems will also provide an initial barrier to erosion. Vegetation will comprise indigenous shallow rooted species. The depth of top soil proposed is sufficient to ensure that adequate water is present to sustain plant growth during dry periods.);

- a layer of markers to minimize the potential for human intrusion;

- a layer of hard cobbles to provide a physical barrier against erosion and intrusion. (Markers may be sandwiched within the cobble layer to ensure that not all the markers are removed in the event of erosion.);

- a graded sequence of free draining sand and gravel to promote lateral flow of infiltrating rainwater;

- a composite layer of clay sandwiched between two flexible membranes and incorporating a reinforced geogrid (Whilst the man-made components may only have a relatively short durability, they are expected to remain effective during the early life of the cap whilst final settlement of the waste takes place. A discontinuity will be incorporated into the clay layer to permit venting of degradation gases from the apex of the cap. A cowl of clay prevents rainwater infiltration.);

- a conductive layer of sand, gravel and, possibly, a water conducting material such as diatomaceous earth for gas collection and routing and to encourage lateral flow of any water that penetrates the impermeable layer;

- fill material to generate the cap profile.

The cap as configured above contains a number of barriers to prevent water impacting on the waste. The first of these is the vegetative cap which will reduce the amount of rainfall which is hydraulically effective through evaporation and evapotranspitration. The shape of the cap itself acts as a barrier by promoting surface runoff. There are two capillary breaks, one above the cobble layer and one below the resistive layer which will serve to intercept infiltrating rainwater. There are three resistive layers, two of man made materials and one of clay, and there is a drainage layer above the resistive layer to prevent the accumulation of standing water. Surface runoff will be collected at the cap perimeter and discharged into the local surface watercourse.

Of note is the potential role for and use of markers to maximize the potential for memory and control of the site to continue for as long as possible in order to further minimize the residual potential impact from human intrusion into the wastes. Markers, either on or off site structures or both, would be intended to signify the presence and characteristics of the site. Markers would be designed so that they protect both low and high technology societies from these risks and would be relevant only if they are likely to survive and be recognizable over periods of thousands of years. If markers are to be successful they need to indicate not only the presence of the site but also some indication of the risks associated with its excavation. This means that markers need to be sufficiently sophisticated that they communicate a clear message.

The long term survival of markers is also of course crucial to their effectiveness and care will need to be given to their size and the materials of construction. Markers may therefore comprise one or more of the following: a large scale marker, for example a large earth mound perhaps supplemented by a limited number of large monolithic markers at strategic locations; smaller scale above-surface markers describing the site characteristics on their outer surface; and/or buried markers distributed over the area of the site and giving information as to its characteristics. Consideration of the need and value of such markers is as yet at an early stage. The issues of both institutional controls and the role of markers is a topical one internationally and which it would be valuable to see a consensus develop in view of the long term nature of this topic and the need for a degree of societal acceptance of their role.

2.2 Cut-off barriers

The final site closure system may include the placement of cut-off barriers around the disposal area and beneath the cap. There are a variety of potential cut-off barriers but the one currently under consideration is a combination of a conventional cut-off wall composed of a low permeability bentonite enhanced soil and a protective band drain. The band drain is placed between the cut-off wall and the waste. In this configuration the band drain can intercept any residual water which does pass through the cut-off wall and at the same time reduce the amount of waste-derived leachate which comes into contact with the cut-off wall. The band drain could potentially be constructed as a gravel-filled drain protected on either side by a coarse sand filter layer. This configuration has the advantage that if the cut-off wall cracks, the drain would still be in place to intercept incoming water and any outflowing leachate. The band drain would be constructed so that it is in contact with both the capillary break below the resistive layer in the cap and the engineered drainage. In this configuration any infiltration which passes the resistive layer would be intercepted, channelled around the waste and out of the site via the engineered drainage. This cut-off barrier concept is however at a relatively early stage of consideration and it will be important to carefully evaluate its performance relative to that of the cap and the resulting potential for bathtubbing.

3. Conclusion

Following installation of the closure measures, a period of maintenance and monitoring is anticipated. Monitoring and security will then be maintained until such times as the results confirm that the facilities have stabilized sufficiently that the residual risk, as evaluated by a final safety case, demonstrates that restrictions on access to the site are no longer required. At that time, the final records associated with the site will be completed and lodged with the appropriate regulatory authority.

The purpose of a site development plan is principally two fold. Firstly, to outline the current strategy relating to both the operation (although not included in this appendix) and closure of the Drigg site. It can be noted that the site development plan forms the main basis for the business plan for the site on which principal funding is made to ensure the necessary financial provision is available throughout the site's lifetime. Secondly, the development plan forms a basis on which to carry out engineering performance evaluation and radiological assessment studies. The former will drive the development of more specific and detailed closure plans and designs. The latter will also be used to assess and optimize potential alternative development plans.

UNITED STATES OF AMERICA

STATUS OF COMMERCIAL LILW SITE CLOSURES IN THE USA

1. Considerations for designing disposal facilities for arid versus humid environments

The United States has adopted the requirements of 10 CFR Part 61 for the licensing standards of all new commercial low level radioactive waste disposal facilities. In general, low level waste as addressed in 10 CFR Part 61 is that waste that is not classified as high level waste, transuranic waste, or naturally occurring or accelerator produced radioactive materials. The requirements of this regulation dictate that certain standards be met by any new licensed facility. Obviously, arid locations offer certain advantages over humid locations with regards to controlling moisture infiltration and movement, the primary mechanism for radionuclide transport. Whereas relatively simple thick vegetated caps designed for enhancing evapotranspiration may be suitable for arid locations, more humid facilities may require more elaborate means to provide for the same degree of long term isolation of wastes from the biosphere. In general, the closure systems at low level disposal facilities built in humid areas of the United States tend to have more engineering features than those in more arid locations.

2. Commercial LLW waste sites

Sheffield, Illinois — The Sheffield facility is in full closure status, awaiting transfer to the custodial agency. There are currently four full-time employees and one part-time employee at the facility engaged in environmental monitoring, maintenance, and custodial activities. Environmental monitoring indicates that the facility is in compliance with the criteria specified in 10 CFR 61.4 1. The site operator, US Ecology, was determined to have met a ten-year commitment initiated in May, 1988 to close, monitor, and maintain the facility. Following this ten-year period, the facility is to be transferred to the Illinois Department of Nuclear Safety (IDNS), the designated custodial agency.

Maxey Flats, Kentucky — Under EPA oversight, the parties potentially responsible for site contamination conducted an intensive study of the contamination problems. This study was completed and a remedy was selected in 1991 and issued as a Consent Decree in 1995. The remedy entails remediation by extracting and solidifying approximately 11 million liters of radioactive trench leachate and disposing of the solidified leachate in on-site earth mounded concrete bunkers. An initial cap consisting of clay and a synthetic liner will be installed to minimize infiltration and leachate generation. The synthetic liner of this initial cap will be maintained and periodically replaced as necessary. The existing site drainage will be improved along with recontouring the capped disposal area to control surface water runoff. A groundwater flow barrier will be installed if necessary as well as an infiltration monitoring system to verify the cleanup performance. Installing a final cap over the disposal area is planned once the infiltration of moisture and leachate generation has been controlled. A buffer zone will be established adjacent to the site, along with establishing institutional controls to restrict the uses of the site. The site will be evaluated every five years to ensure that the remedy continues to be effective.

In 1996, the Initial Remedial Phase Design Work was completed and approved and construction of the bunkers began in 1997. The Phase I bunker construction, the batch mixing facility for trench leachate, and installation of the leachate transfer system should be completed during the summer of 1998. Pumping, solidification, and disposal of trench leachate should begin in the fall of 1998.

Beatty, Nevada — The Beatty, Nevada LLRW facility ceased accepting radioactive waste for disposal in December 1992. The site operator, US Ecology, began closure activities in December 1993, completing all physical work items in the approved site closure and stabilization plan in July 1994. No environmental remediation was required during site closure. The following 30 months were used to control, maintain, and monitor the facility.

Documentation of waste receipt and operations were also compiled and filed with the state during this period. The State of Nevada voluntarily accepted custody of the site on December 30, 1997, making the Beatty site the first commercial LLRW facility to be successfully closed and readied for long term custodial control by a state agency. The facility meets the performance objectives of 10 CFR 61.41. Long term care activities conducted by the State of Nevada include quarterly environmental monitoring and site surveillance.

West Valley, New York — In spring 1997, the New York State Energy Research and Development Authority (NYSERDA) completed three projects designed to reduce or eliminate water infiltration in the state-owned commercial LLRW disposal area (SDA). These projects included a slurry wall and geomembrane enhanced cover for Trench 13/14; a bioengineering cover using selectively planted shallow rooted plant species, and extension of geomembrane cover over Trenches 1–8, 10, and 11 and the grass-covered portion of 12. Results indicate that infiltration and leachate generation have subsequently declined as a result of this work.

Since the completion of the infiltration controls work, activities at the SDA have focused of routine environmental monitoring, and routine inspection and maintenance. One minor erosion mitigation project involving lining a drainage pathway with prefabricated concrete blocks cabled together to form a waffle-like mat.

The NYSERDA is working with the USDOE on the Environmental Impact Statement for Completion of the West Valley Demonstration Project and Closure or Long term Management of the Facilities at the Western New York Nuclear Service Center. The Environmental Impact Statement (EIS) assesses closure options for the entire West Valley facility, including the Surface Disposal Facility. The Draft EIS, issued in 1996 assessed five options: exhumation and off-site disposal; exhumation and on-site storage; in-place closure; ongoing maintenance of existing facilities; and site abandonment (discussed only for comparison purposes). As of this date, the NYSERDA and the USDOE have not selected a preferred alternative pending input from the Citizen Task Force.

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