

CONCEPTUAL DESIGN AND PERFORMANCE ASSESSMENT OF A DEEP GEOLOGICAL REPOSITORY FOR HIGH-LEVEL NUCLEAR WASTE IN KOREA

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Abstract

The conceptual design for an underground spent nuclear fuel repository in Korea is described in this paper. The major factors that influenced the base case conceptual design include waste package size and weight, waste package thermal output, waste package receipt and emplacement rate(s), vertical borehole emplacement, and geologic setting of the conceptual repository in terms of rock type, water conditions, topography, and rock quality. Although not sited, the conceptual repository was designed to be located in granitic rock at a depth of nominally 500 m between two large fault zones that extend from depth to the surface. The geologic repository system conceptual design includes surface and underground operations and facilities, as well as access construction. The engineered barrier system, composed of waste forms, surrounding waste package, and buffer and backfill material, provides the primary containment and is protected by the natural barrier system. A multi-stage approach is recommended for moving from the conceptual repository design to a Phase 2 reference design that will be validated in preparation for the formal license application.

Introduction

The Republic of Korea began operating commercial nuclear power plants with the commissioning of the 595 MW Kori-1 reactor in 1978. Today, Korea's nuclear power program has fifteen operating plants, four Canadian deuterium-uranium (CANDU) and eleven pressurized-water reactor (PWR) designs, which generate approximately 13,700 MWe. Figure 1 shows the accumulated amount of spent fuel annually generated from 1979 to 1997. By the end of 1997, total amount of spent PWR fuels is 4434 assemblies (about 1950 tHM). The corresponding amount of CANDU fuel is about 1371 tHM. Korea's long-term plan is to double nuclear energy generation by 2015 with 27 reactors operating reactors. This dramatic growth in nuclear energy production, coupled with the aging reactors, planned decommissioning of existing reactors, and the long lead time required to bring a repository on line, highlights the need to develop plans for spent nuclear fuel (SNF) disposition in Korea. Without available safe storage capacity, transportation systems, and permanent disposal capabilities, continuous operation of on-line plants could be jeopardized.

Korea's nuclear policy calls for early repository planning, and a program is in place to establish a reference high-level waste repository concept by 2006. The program plan defines three, three-year phases: *Phase 1 – Concept Development; Phase 2 - Reference Repository System; and Phase 3 - Korean Standard Repository*. The Korean Atomic Energy Research Institute (KAERI) began work on this HLW disposal technology research and development program in 1997, and this paper summarizes the results of Phase 1. It provides a preliminary repository conceptual design that will be used as a baseline for Phase 2 efforts.

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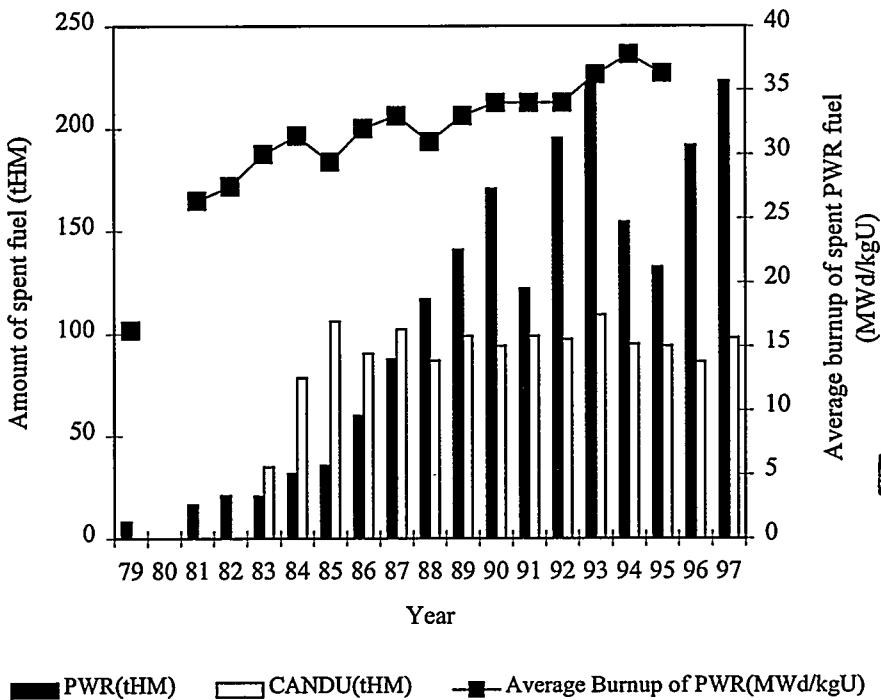


Figure 1. Spent fuel inventories annually generated from the Korean Nuclear Power Plants and the trend of the average discharge burnup.

This conceptual design addresses all the repository design and performance assessment components needed to support the Reference Design, a more detailed definition of the repository system. In addition, this preliminary conceptual design identifies important assumptions and qualitatively considers alternative designs and scenarios that validate the use of the selected design parameters.

The preliminary conceptual design contains the following:

- descriptions of the critical elements of the underground repository facility, waste package/canisters, and surface facility designs;
- discussions of the design bases and assumptions;
- descriptions of the surface and underground systems;
- descriptions of the engineered barrier system including waste package design and material selection;
- descriptions of construction and operation concepts;
- descriptions of design flexibility, alternatives, and sensitivity analysis in terms of the cost and safety; and
- recommendations for future work in Phase 2.

This conceptual repository design provides a good first estimate of functionality, cost, and safety to the public and the environment. The conceptual design basis consists of information regarding specific functions of the repository and design requirements consisting of basic assumptions and technical criteria developed from fuel cycle and regulatory criteria.

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These criteria include

- characteristics of SNF (e.g., initial enrichment, burnup rates, cooling time, thermal load, physical condition, and containment characteristics);
- design of surface facilities (e.g., spent fuel receiving, spent fuel conditioning, spent fuel storage, spent fuel packaging and handling, buffer plant, concrete plant, monitoring system, and repository access);
- design of the underground facility (e.g., access design, panel layout, mine construction techniques, spent fuel emplacement, backfill design, closure, retrieval, and monitoring);
- repository geologic setting (e.g., general lithography, fault characteristics, and groundwater flow characteristics);
- performance assessment (e.g., general approach, key input parameters, sensitivity analysis, alternative scenario development, and parameter sensitivity analysis);
- regulatory environment (e.g., deterministic versus probabilistic performance assessment and maturity of regulations); and cost estimates.

It is important to recognize the limitations of the repository conceptual design. In the preliminary conceptual design phase, data specified for the above criteria are necessarily flexible. In many cases, specific values are unknown, and, therefore, are assumed. In other cases, new scientific information may become available or conditions may change that warrant adjusting particular data values. This preliminary design is not site specific, there are no site characterization data that tie repository performance to a specific location; therefore, design parameters and performance assessment criteria are necessarily general in nature.

The preliminary design defines the project feasibility and provides assurances that further work is warranted and can proceed with a high degree of confidence. Phase 2 design activities may result in modifications to this preliminary design that will reflect a deeper understanding of all the initial input with respect to any changes. Repository conceptual design modification may be due to refinement of data or concepts, inclusion of uncertainty associated with data values, new scientific evidence, new or revised regulations, programmatic re-direction and/or shifts in governmental policy reflecting the natural evolution from preliminary to final design. It is also important to closely investigate international repository concepts and safety/technical criteria.

Thus, the preliminary design presented in this paper provides a baseline design that defines the functionality of the repository, provides general costs, and evaluates safety aspects during operations and after closure of the repository. Because of the high level of uncertainty in several key design features, including waste package, borehole configuration, and repository layout, the conceptual design must be iteratively revised until the uncertainties are resolved.

Design Bases

The repository conceptual design begins with the selection of reference spent fuel to be disposed, followed by the determination of basic assumptions and governing criteria. The next step is the determination of the most promising fuel packaging options and underground repository layout options. Finally, a preliminary conceptual design of the repository is developed.

The design process followed the repository design bases:

- design requirements,
- primary design assumptions
- required pre- and post-closure system functions, and
- key pre- and post-closure goal and objectives.

These design bases provide the information that identifies the specific functions to be performed by the repository system, as well as the specific values or ranges of values chosen as controlling parameters to bound the design.

According to the design assumptions and criteria, the conceptual repository will be located in granitic rock, major rock type in Korea [1], at a depth of nominally 500 m between two large fault zones that extend from depth to the surface. The rock quality varies from highly weathered surface deposits to competent rock at the repository horizon. For this conceptual design, the distance between faults is about 7–10 km. Therefore, the repository layout must be capable of fitting within these major structural features. The most stringent requirement for the base case underground facility is that the temperature of the bentonite buffer material remains below 100°C throughout the lifetime of the repository.

The development of the underground repository system conceptual design required specifications of (1) design constraints and criteria, (2) disposal canister design, and (3) waste form and throughput.

These key design constraints include:

- Waste inventory; 36,000 MTU (20,000 MTU of PWR and 16,000 MTU of CANDU spent fuel),
- Emplacement sequence: CANDU spent fuel first, followed by PWR spent fuel,
- Backfill design: vertical boreholes with bentonite buffer,
- Repository layout: single-level repository,
- Throughput: dictated by a 50-year operational life of repository,
- Thermal constraints: surface temperature of disposal container limited to 100°C,
- Waste package configuration: 4 PWR assemblies and 333 CANDU bundles,
- Borehole spacing: 3 m (CANDU) and 6 m (PWR), and
- Drift spacing: 40 m.

Repository System Design

The major factors that influenced the base case conceptual design include waste package size and weight, waste package thermal output, waste package receipt and emplacement rate(s), vertical borehole emplacement, and geologic setting of the proposed repository in terms of rock type, water conditions, topography, and rock quality. Figure 2 shows the suggested iterative process that illustrates how the design of various repository system components are based on the design of upstream system components. The geologic repository system base case design includes surface and underground operations and facilities as well as access construction.

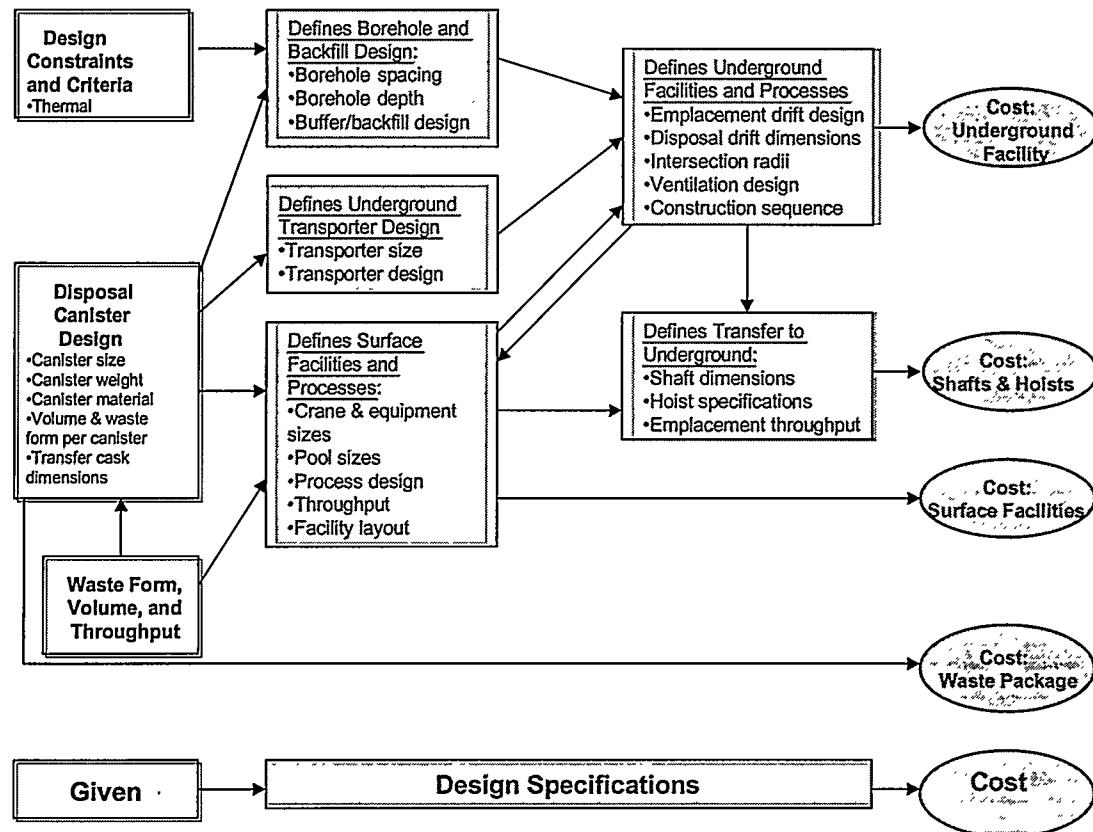


Figure 2. Flow diagram for geologic repository system design.

Surface Facilities

The surface facility layout shown in Figure 3 is functional in nature with required surface facilities, buildings, features, and locations identified as reasonably as can be expected for a preliminary conceptual design. Given that the surface facilities are derived from the underground design, it is premature to design more detail into the surface facilities until underground facility design trade-off studies are completed. The actual surface facility layout will be developed during detailed design phases of the project so that (1) the surface facilities are fully integrated with the subsurface functional layout, and (2) the surface structures are self-integrated and conform to site topographic features.

In the repository conceptual design, the surface facilities receive the spent fuel from the transportation system, unload the spent fuel into a receiving pool, repack the spent fuel into the disposal container, provide temporary storage (i.e., lag or surge storage), and transport the disposal canisters to the entrance of the repository for emplacement. The surface facilities process flow is designed to accommodate the underground facilities requirements for transport, emplacement, and performance of the waste disposal canister.

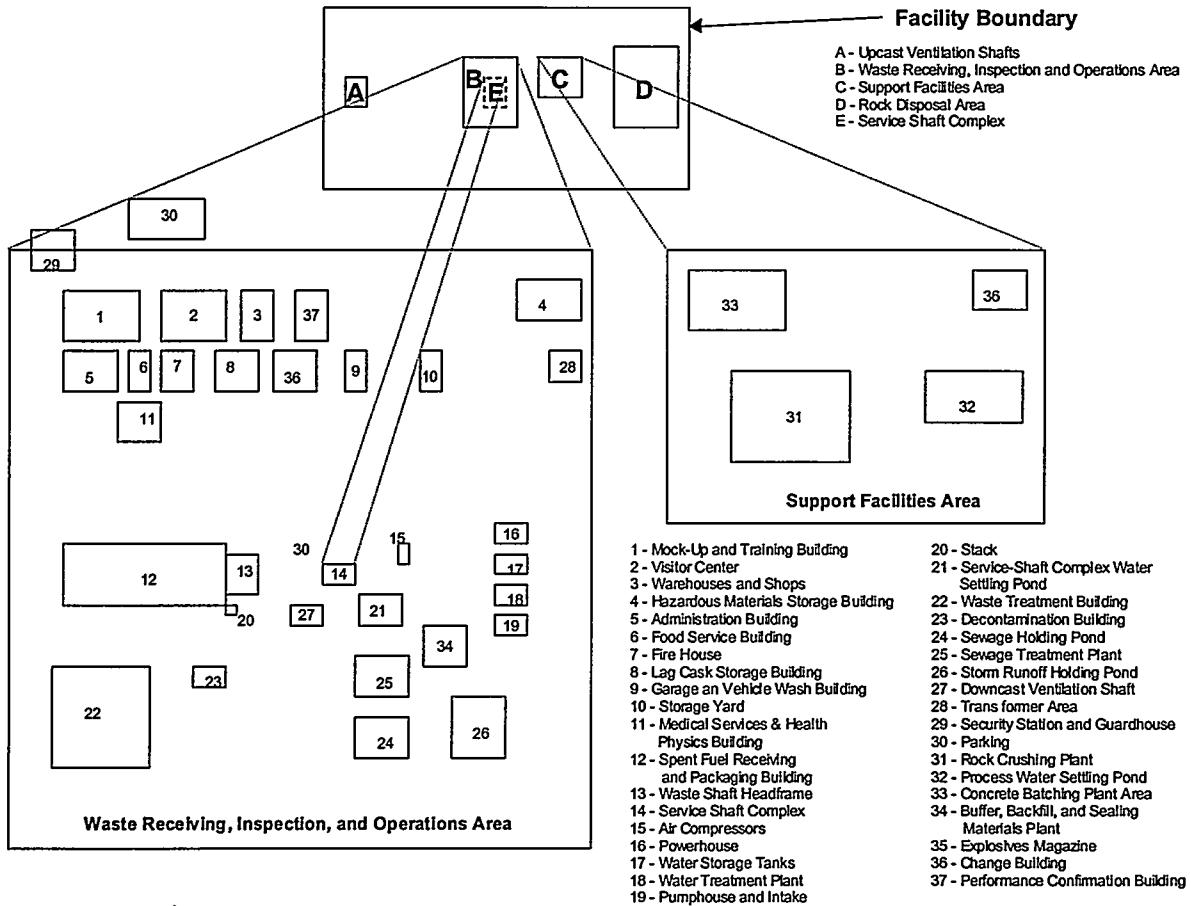


Figure 3. Layout of surface facilities to support underground operations.

Underground Facilities

The conceptual repository layout builds on the information and key constraints that define the emplacement tunnel dimensions and borehole separation distances, borehole layouts and waste-receipt schedules. Figure 4 shows the isometric view of the various underground openings including the disposal area, the service shaft complex, and the ventilation exhaust shaft complex. The entire facility is assumed to be constructed using drill and blast techniques. Drill and blast construction allows flexibility of layout with the least amount of wasted space with excavations intersecting at right angles. The layout also assumes that the CANDU waste will be emplaced separately from the PWR waste. A separate CANDU emplacement area is identified at the lower left of the layout nearest the ventilation shaft complex.

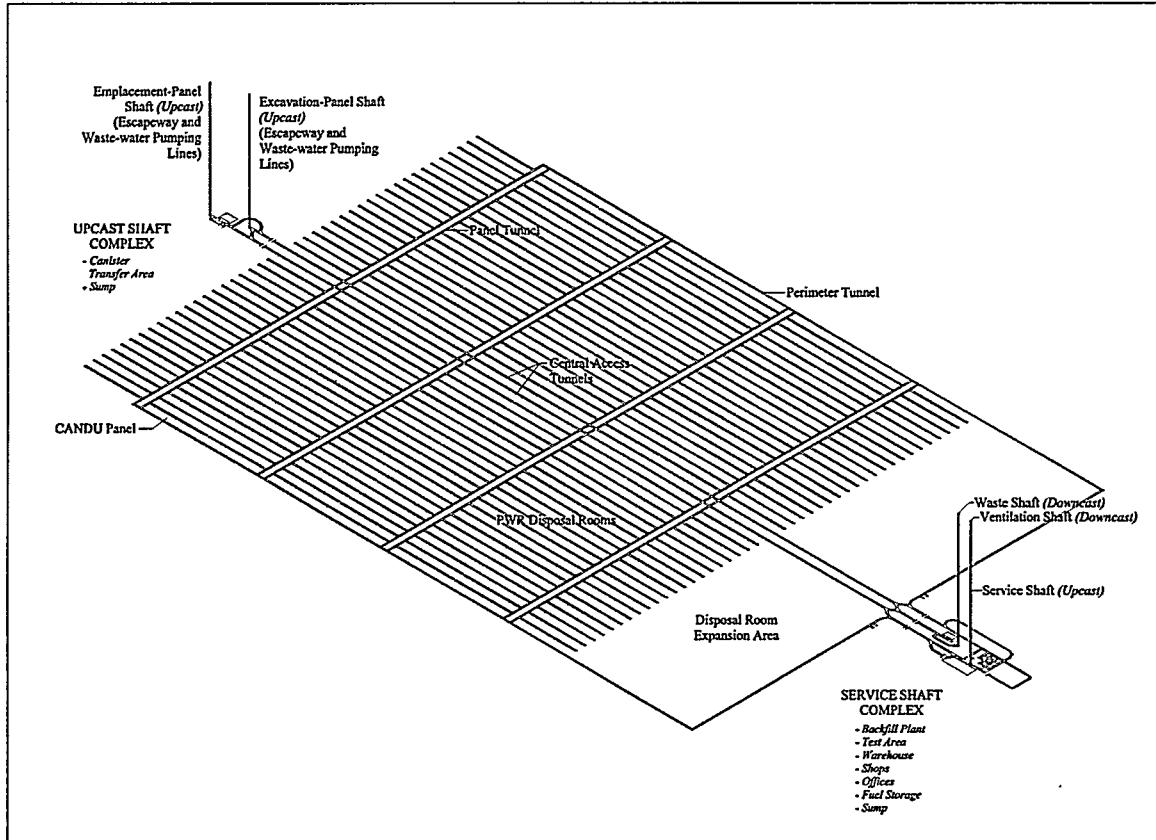


Figure 4. Isometric view of the preconceptual base case KAERI repository.

Engineered Barrier System

For this preliminary conceptual design, the repository containment concept engineered barrier system provides the primary containment and is protected by the natural barrier (i.e., the geological formation) system. The engineered barrier system is composed of the waste forms, surrounding waste package, other man-made items in the underground facility, and buffer and backfill material. Design features of the engineered barrier system are waste form, waste canister package, and bentonite buffer [2]. Figure 5 shows the wasted package and engineered barrier design concept for the Korean repository.

The reference spent PWR and CANDU fuels are defined in terms of initial enrichment, burnup rates, dimension, gross weight, etc. As a design basis, spent fuel inventories are estimated to be 36,000 tHM, based on the Nuclear Energy Plan of the Long-Term National Power Development Plan. PWR fuels comprise approximately 20,000 tHM (55% of total inventory to be disposed) of the projected spent fuel inventory. The reference PWR spent fuel has the average burnup of 45,000 MWd/tHM (initial enrichment of 4.0 wt%) and is cooled for 40 years after irradiation before the encapsulation and disposal. An alternative burnup level is 55,000 Mwd/tHM. PWR assembly weight and dimensions are 665 kg and 21.4^2 cm^2 (cross-section) x 453 cm (length), respectively. The spent CANDU fuel inventories are approximately 16,000 tHM, 45% of total inventory to be disposed. The reference CANDU fuels have the average burnup of 7,500 MWd/tHM and the fuel dimensions are 10 cm (diameter) x 49.5 cm (length).

Proposed KAERI Waste Package Degradation

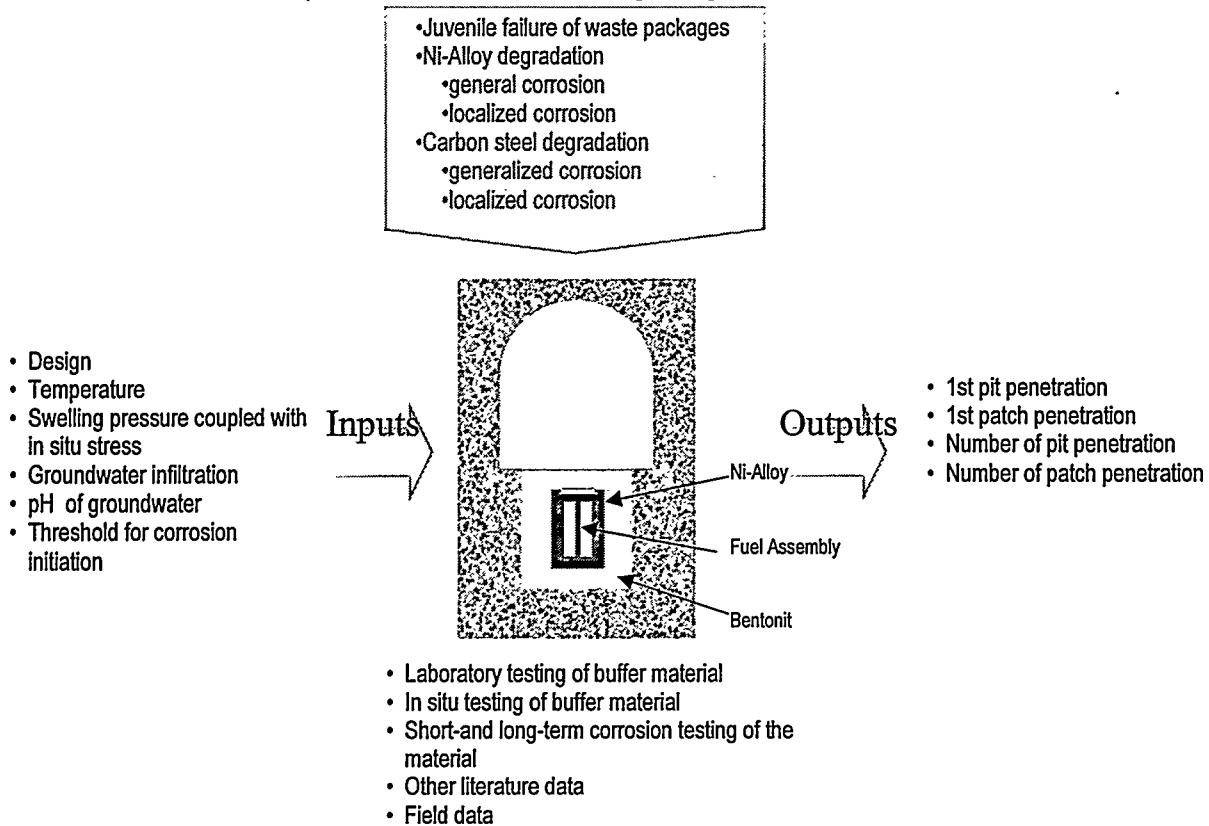


Figure 5. Engineered barrier design concept for the Korean repository.

Although no specific materials are recommended for the Korean repository, copper, high-nickel alloy (Alloy-22), or stainless steel are under consideration for the outer shell of the Korean waste package. Until a specific site for a Korean repository is selected, and conditions within such a repository can be estimated within a given level of uncertainty, selection of waste package materials for a Korean repository remains speculative.

Bentonite is under consideration as the buffer material because of its slow permeability, high sorption capacity, self-sealing characteristics, and durability. The need for, extent, and required performance of seals in the underground facilities and access shafts and ramps for the Korean repository must be developed as a result of performance assessments of the system. The Korean concept includes borehole emplacement in the floors and subsequent backfilling of the emplacement tunnels. To provide confinement and security for the backfill and tunnel, a concrete bulkhead would be installed at the entrance to each emplacement tunnel (at the Panel Tunnels) to confine the backfill materials and restrict access into the completed emplacement tunnels. The base case repository includes backfilling, particularly of the emplacement tunnels, immediately after waste emplacement. The backfilling is intended to provide additional support for the underground openings. The backfill composition must be determined through more detailed performance assessments and engineering trade-off studies.

Exploration, Construction, Operation, and Decommissioning and Closure Concepts

The exploration, construction, operation, and decommissioning and closure of the Korean base case conceptual repository are discussed in terms of process and sequence of operations. The repository life cycle sequence is divided into four phases. Phase 1 is defined as the repository exploration sequence. Phase 2 is termed the repository construction sequence. Phase 3 is the repository operations sequence, and Phase 4 is the decommissioning and closure stage.

The surface waste handling facilities are designed to receive the spent fuel from the transportation system, unload the spent fuel into a receiving pool, repackage the spent fuel into the disposal container, provide temporary storage (i.e., lag or surge storage), and transport the disposal canisters to the entrance of the repository for emplacement. The base case design allows for two separate process lines: one for CANDU fuel, and one for PWR fuel. The CANDU and PWR waste will arrive at the Spent Fuel Receiving and Packaging Building (SFRPB) in transportation casks. Although both waste form will be handled and packaged in the SFRPB, because of the great variation in size, radiation levels, and packaging processes of the two waste forms, CANDU and PWR fuel will be handled and packaged using different equipment. The CANDU and PWR fuel will share a receiving pool, and CANDU and PWR canisters will use the same surge-storage pool.

Monitored Retrieval Operation program will monitor for unexpected radioactivity and provide warning for the underground and surface facilities. These monitoring systems should sample the air at locations throughout the repository for radionuclides and provide an alarm to allow for control measures to be initiated. The control of inadvertent radionuclide releases is, under normal operating conditions, through the use and activation of the high-efficiency particulate air (HEPA) filtration system located at the surface facilities of the upcast emplacement shaft. The Korean repository design should include detailed plans for remediation under alarm conditions. Decommissioning and closure of the Korean base case repository will occur following emplacement and monitoring. Safety analyses will determine whether the site is performing as predicted.

The retrieval process concept is not simply a reversal of the emplacement process, because the emplacement tunnels may be backfilled and plugged at the entrance. In addition, depending on the time of retrieval, the materials may have heated to above ambient temperatures by radioactive decay of the emplaced waste. Therefore, the retrieval process includes aspects of mining combined with reverse emplacement.

The performance confirmation (PC) program is an integral part of the licensing process for a geologic repository. For the U.S. repository program, 10 CFR 60 (part 140 through 143) [3] describe performance confirmation program requirements for the complete performance confirmation program. Specific details regarding the performance confirmation program will be developed concurrent with site characterization activities at the Korean site. The goal of the performance confirmation program is to determine with reasonable assurance that the performance objective(s) for the proposed repository for the period after permanent closure will be met. The general objectives for the performance confirmation program are (1) acquire data, (2) use the acquired data in assessments to ensure that the repository systems are functioning as intended and anticipated, and (3) support subsequent applications to support amendments to the license for permanent closure of the proposed repository.

Cost Analysis

Repository design and costing is an iterative process: changes in upstream system component designs or criteria will cause changes in nearly all downstream system design components and costs. For example, the borehole and backfill system design features like borehole spacing and depth are based on design constraints and criteria such as the 100°C canister surface thermal constraint and canister design such as dimensions, material, and waste form. Similarly, the disposal canister design specifications are key factors in (1) the underground transporter and shielding cask design, and (2) the waste handling and packaging portion of the surface facility design. In turn, the design of the underground facilities and processes depends upon the borehole and backfill design, the underground transporter design, and the surface facility design and throughput. Therefore, changes in the disposal canister design will result in changes to the borehole and backfill design, changes to the underground transporter design, and changes to parts of the surface facility design, all of which will cause changes in the design of the underground facilities and processes. The total cost for the base case repository system is the sum of the costs of the Underground Facility, Shafts and Hoists, Surface Facilities, and Waste Packages.

The total cost for Site Preparation activities is estimated to be 412.8 million \$US, and the total cost for Surface Facilities is estimated to be 2.55 billion \$US. The total cost for Underground Facilities is estimated to be 2.81 billion \$US, and the total cost for the Waste Canisters is estimated to be 5.38 billion \$US. The Total System Life Cycle Cost for the base case repository is 11.15 billion \$US. The cost estimates are in year 2000 \$US, and future costs are not escalated. The annual cost distribution for the proposed Korean repository life cycle is shown in Figure 6.

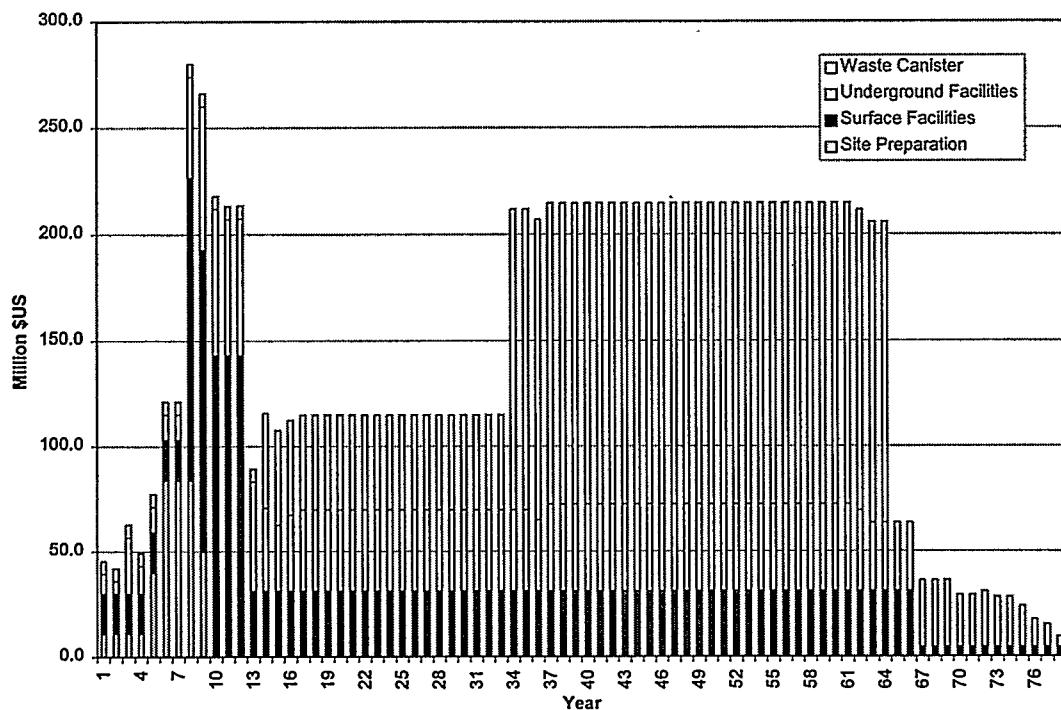


Figure 6. Annual cost distribution for repository life cycle.

Estimates of surface facility costs are considered preliminary. The Underground facility costs, which focus on preliminary capital cost estimates, are also considered preliminary. The Package Total System Life Cycle Costs (TSLCC) include the major cost accounts for Siting and Licensing, Construction, Operation, and Decommissioning and Closure.

The surface and underground facility costs are presented in top-level summary form with a year-to-year cost breakdown. The costs are presented in terms of the four major phases of repository operation: Exploration, Construction, Operation, and Decommissioning and Closure. The Exploration phase include parts of design, siting, and licensing of on-site and off-site surface facilities and infrastructure. The Construction phase includes construction of all surface waste handling and support facilities. The Operation phase includes receipt, handling, encapsulation, monitoring, and emplacement of the waste. The Decommissioning and Closure phase follows the operations phase.

The surface facility cost estimates are based on published cost estimates for the Yucca Mountain Project and SKB's estimated costs for management of the radioactive waste from nuclear power production in Sweden [4-7]. The waste canister costs for the Korean repository were calculated using estimates for design, material, and fabrication costs based on the design specifications.

In addition to those costs directly associated with the surface and underground facilities and waste canister fabrication, many other costs should be considered when designing an underground spent fuel repository. These additional costs include repository development and evaluation costs; performance confirmation costs; regulatory, infrastructure and management services costs; waste acceptance, storage, and transportation costs; program integration costs; and institutional costs.

Discussion and Conclusions

There is a demonstrated need for a SNF repository in Korea. A high-level sensitivity analysis of the base case was performed to evaluate the design concept in terms of cost, worker safety, and schedule. Cost, worker safety, and schedule were qualitatively evaluated on the basis of repository depth, a multi-level versus a single-level repository, and the use of a multi-purpose canister/cask versus single-use cask and canister. The results of this high-level analysis support the further development of the repository design concept.

A multi-stage approach is recommended for moving from the base case repository design to a Phase 2 reference design that will be validated in preparation for the formal license application. Stage 1 consists of refining the conceptual repository design and philosophies, development of approaches to programmatic systems, and parametric analysis. Stage 2 consists of a formal evaluation of the repository design with respect to the natural and engineered systems, development and implementation of performance assessment models and codes, the initiation of experimental test programs, and the implementation of model, software, and data management systems. Stage 2 culminates with Reference Design for the repository in 2007. Stage 3 consists of experiment and model validation of the Reference Design to support the License Application calculations in Stage 4.

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