DISPOSAL VAULT ALTERNATIVES IN THE CANADIAN NUCLEAR FUEL WASTE MANAGEMENT PROGRAM

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ABSTRACT

In the Canadian Nuclear Fuel Waste Management Program, AECL and Ontario Hydro are studying the feasibility of engineering the surface and underground facilities necessary to receive, package and dispose of nuclear fuel waste at a disposal site, and the vault sealing systems to aid in its containment. This paper presents the disposal vault arrangements and waste emplacement configurations that have been considered. Two conceptual design studies of disposal facilities are discussed, one completed and one in progress. The discussion emphasizes the disposal vault arrangements, the waste emplacement configurations and the sealing systems proposed as barriers. The estimated resource requirements for implementing one of the conceptual designs are also presented.

INTRODUCTION

Atomic Energy of Canada Limited (AECL) and Ontario Hydro have been developing and assessing the technologies for the safe geological disposal of CANDU* reactor nuclear fuel waste in the Canadian Nuclear Fuel Waste Management Program (CNFWMP). The results of this program are the subject of a technical and public review beginning in 1994. The report on this review will be submitted to the governments of Canada and the Province of Ontario, and will contribute to a decision concerning the future direction of nuclear fuel waste management.

In this review a method for geological disposal of nuclear fuel waste is proposed in which:

- the waste form would be either used CANDU fuel or solidified highly radioactive reprocessing waste;
- the waste form would be sealed in a container designed to last at least 500 years and possibly much longer;
- the containers of waste would be emplaced in rooms in a disposal vault or in boreholes drilled from the rooms;
- the vault would be nominally 500 to 1000 m deep;
- the geological medium would be plutonic rock of the Canadian Shield;
- each waste container would be surrounded by a buffer;
- each room would be sealed with backfill and other engineered seals; and
- all tunnels, shafts, and exploration boreholes would ultimately be sealed so that the disposal facility would be passively safe, that is, long-term safety would not depend on institutional controls.

The disposal vault would be a network of horizontal tunnels, disposal rooms and service areas excavated deep in the rock, with vertical shafts extending from the surface to the vault level. Rooms and tunnels could be excavated on more than one level. This room-and-pillar arrangement, widely used in underground excavation, offers modularity in design, flexibility in the spacing of disposal rooms and of disposal containers within the rooms, and flexibility in size, shape and orientation of the excavations. The disposal containers, the disposal vault and the vault seals would be designed for the rock structure and other underground conditions at the disposal site.

When the disposal vault is closed, there would be multiple barriers to protect humans and the natural environment from both radioactive and chemically toxic contaminants in the waste. These barriers would include the waste form; the container; the buffer, the backfill, and other vault seals; and the geosphere.

A number of scoping studies have been done to assess the construction, operation and thermal and thermal-mechanical performance of various disposal vault arrangements and waste emplacement configurations. One conceptual design study has been completed for a disposal vault using the in-floor borehole emplacement configuration and a second is now in progress for a disposal vault using the in-room emplacement configuration.

SCOPING STUDIES

Scoping studies have been done for a variety of disposal vault arrangements and waste emplacement configurations to provide insight into their relative advantages and disadvantages. The scoping studies have been discussed by Baumgartner and Simmons (1) and are only briefly summarized here. The thermal-mechanical specifications for the rock mass and the sealing materials have evolved during these studies so the results of individual studies cannot be compared in detail. In particular, the maximum temperatures on the outer surface of any disposal container has been reduced from 150°C to 100°C, a maximum temperature of 100°C has been instituted for the buffer material, and the volume-averaged backfill temperature limit and sustained long-term, far-field temperature limit have been dropped. As well, the assumed in situ stress conditions and rock mass failure criteria have become more representative of in situ conditions based on experience in the Underground Research Laboratory. These scoping studies contributed information and understanding that has guided the choices made for the conceptual design studies that followed. The alternatives discussed in this section are shown in Fig. 1.

* CANDU (CANada Deuterium Uranium) is a registered trademark of AECL.

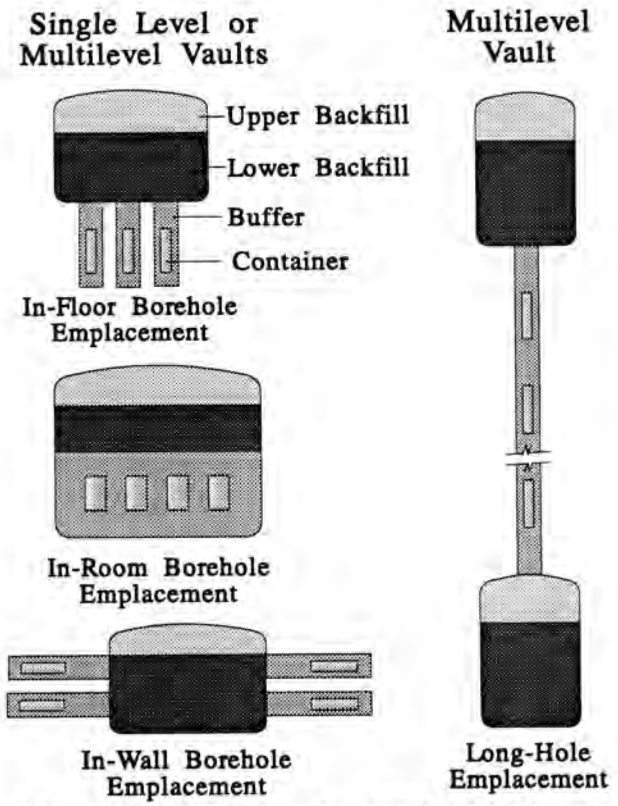

Fig. 1. Waste emplacement and disposal vault alternatives studied in the CNFWMP.

Acres et al. (2,3) completed two scoping studies of single-level disposal vaults: one for disposal of containers of used fuel within the boundaries of a disposal room (i.e., in-room emplacement); and the other for disposal of individual containers of reprocessing waste in boreholes drilled into the floor of disposal rooms (i.e., in-floor borehole emplacement). The results indicated that the thermal and mechanical criteria set for the studies could be satisfied and that these waste emplacement configurations warranted further consideration.

Tsui and Tsai (4) analyzed the thermal and thermal-mechanical differences between two single-level disposal vaults, one using in-floor borehole emplacement and the other emplacing individual waste containers into boreholes drilled into the rock pillars on each side of a disposal room (i.e., in-wall borehole emplacement). These analyses indicated that the in-wall configuration gave lower temperatures but similar stress concentrations. The benefits of the horizontal configuration were limited and were offset by the difficulties associated with handling and placing materials in the horizontal boreholes.

Acres and RE/SPEC (5) studied the multilevel disposal vault arrangement to assess the potential for minimizing the plan area of plutonic rock necessary to disposal of a given mass of nuclear fuel waste. The depth range considered for the multiple levels was from 500 m to 1000 m. For used-fuel containers placed in the in-room emplacement configuration, there was no significant reduction in required plan area between a single-level disposal vault at 1000 m depth and a two-level disposal vault with levels at 500 m and 1000 m. This was because the spacing between the individual emplacement boreholes had to be increased significantly in the two-level arrangement to allow for adequate dissipation of the heat from the used fuel. However, for fuel reprocessing waste the heat output decreases more rapidly and disposal containers in the in-floor borehole emplacement configuration could be placed on three levels at depths of 500 m, 750 m and 1000 m. There was a reduction of more than 65% in disposal vault plan area at less than a 15% increase in capital cost. The multilevel disposal vault configuration warrants further consideration for disposal of reprocessing waste.

Acres (6) studied the possibility of using the vertical dimension of a pluton by placing several disposal containers of used fuel or reprocessing waste in long boreholes drilled between the levels of a disposal vault (i.e., long-hole emplacement) at depths of 500 m, 750 m and 1000 m. Because of the long duration of sustained heat output from used fuel, the horizon and vertical spacing between containers had to be relatively large to satisfy the thermal and mechanical criteria. Disposal of used fuel in the long-hole vault arrangement offered no significant reduction in disposal vault plan area when compared with the multi-level used-fuel disposal vault arrangements. For disposal of reprocessing waste, the long-hole disposal vault arrangement offered a small reduction (10%) in plan area when compared with the multi-level disposal vault arrangement but at a substantially higher cost. The long-hole emplacement does not offer any apparent benefits.

Wardrop et al (7) prepared descriptions of integrated buffer and backfill systems for the used-fuel and reprocessing waste emplacement configurations developed in the scoping studies (2) and (3). Materials acquisition and transport, materials preparation and handling, and buffer, container and backfill emplacement were discussed. The revisions to (2) and (3) necessary to incorporate integrated buffer and backfill systems and placement methods were presented including disposal room preparation, borehole drilling, buffer placement and compaction, augering a disposal container hole into compacted buffer, container placement, final buffer placement and disposal room backfiling and sealing with a bulkhead. This study concluded that the buffer and backfill would be significant components of disposal vault operation and cost.

These scoping studies provided the bases for selecting the disposal vault arrangements and emplacement configurations for the conceptual design studies. The scope of the studies was narrowed when the CNFWMP focussed on the disposal of one waste form, used fuel. One conceptual design study was done for a single-level disposal vault using the in-floor borehole emplacement configuration. A second study is now in progress using a single-level disposal vault arrangement and the in-room emplacement configuration.

A SINGLE-LEVEL USED-FUEL DISPOSAL VAULT USING THE IN-FLOOR BOREHOLE EMPLACEMENT CONFIGURATION

Study Specifications

This Used-Fuel Disposal Centre conceptual design (8) describes a facility that would receive, package and dispose of used-fuel bundles (Fig. 2) irradiated to an average burnup of 685 GJ/kg U and cooled for 10 a after their discharge from a CANDU nuclear power reactor. The capacity of the disposal vault is about 191 000 Mg U in the unirradiated fuel or about 10.1 million used-fuel bundles.

The disposal container is a packed-particulate design (Fig. 2), fabricated from ASME Grade-2 titanium, which holds 72 used-fuel bundles. The annual throughput in the

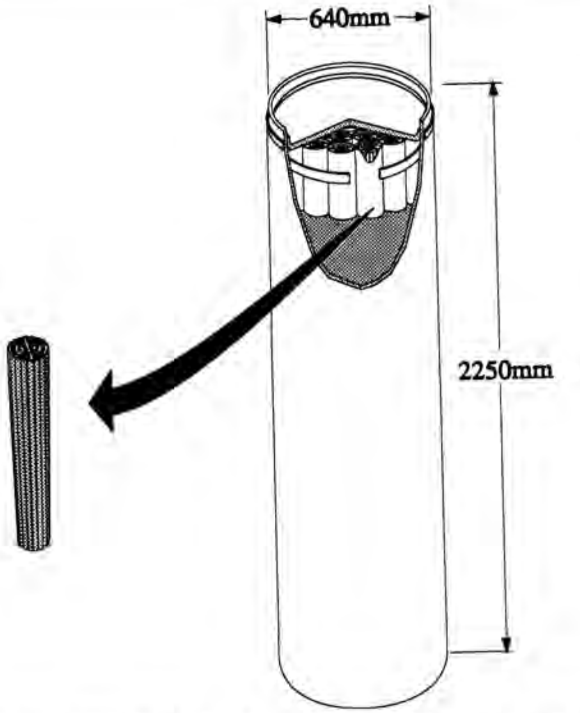

Fig. 2. CANDU fuel bundle and a packed-particulate disposal container design.

conceptual design is about 250 000 used-fuel bundles which is the assumed capacity of the used-fuel transportation system. This fills 3470 disposal containers per year, giving a disposal vault operating duration of over 40 a.

Additional assumptions in this study include the following:

1. The disposal vault will use shafts for access and will be arranged in a single-level room-and-pillar configuration.
2. The emplacement configuration will be in-floor borehole emplacement with a single container in each borehole.
3. The disposal vault will be located at a depth of the 1000 m, although this depth may be changed during design analyses to satisfy the mechanical and thermal-mechanical constraints listed below.
4. The maximum temperature at the outer surface of the container and throughout the buffer material must not exceed 100°C.
5. The average strength-to-stress ratio for the interroom pillars and, where applicable, the rock webs around the waste emplacement boreholes will be two or greater where strength is defined using the Hoek-Brown empirical failure criteria. As well, the extraction ratio on the emplacement level will be about 0.25.
6. The near-surface extension zone, the layer of rock immediately below the ground surface overlaying the disposal vault that could experience the loss of horizontal confining stresses and the potential opening of subvertical fractures due to thermal expansion of the rock around the disposal vault, must not extend more than 100 m below surface.

Facilities Description

The Used-Fuel Disposal Centre developed in the conceptual design is self-contained and located on a suitable plutonic rock body of the Canadian Shield (Fig. 3). It includes a disposal vault excavated into the rock body at a depth of 1000 m, and surface facilities for the receipt and packaging of used fuel in disposal containers and the fabrication of the disposal containers and components. During excavation of the disposal vault, any fractures that have groundwater seepages in excess of those reasonable for operations will be sealed with grout and, if necessary, with shaft or tunnel liners as a construction expedient.

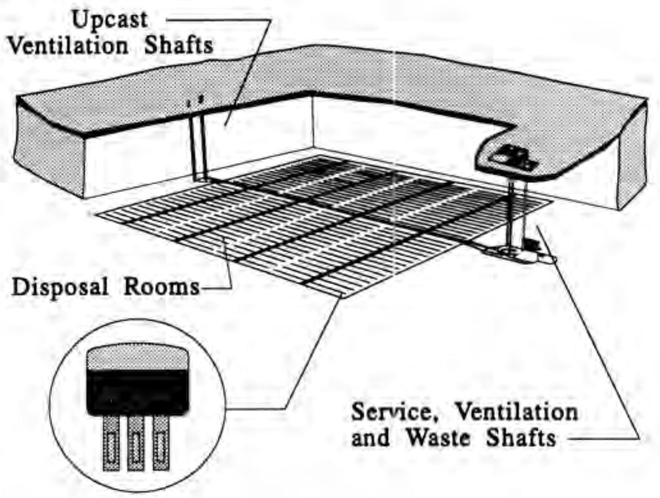

Fig. 3. Disposal center with a single-level disposal vault using in-floor borehole emplacement.

Used fuel is received at the packaging plant of the disposal centre in either a road or rail transportation cask that contains the used-fuel bundles in storage/shipping modules. These modules are unloaded from the casks in a module-handling cell. The modules may be held temporarily in a water-filled pool or they may be transferred directly to the used-fuel packaging cell. In the packaging cell, 72 fuel bundles are transferred from the shipping modules to the disposal container fuel basket and the fuel basket is placed into a disposal container. Each bundle and container is accounted and monitored for nuclear material safeguards purposes during the transfer operations.

The disposal container (Fig. 2) shell and end closures are fabricated of 6.35-mm-thick ASME Grade-2 titanium. The loaded container is filled with an inert particulate, such as glass beads, that is vibrationally compacted to fill all the void space, to allow the container to withstand the expected external loads. A top head is pressed into the container, and the top head and container shell flanges are diffusion-bonded. Each filled container has a mass of about 2800 kg. When initially sealed in the disposal container, the 72 used-fuel bundles produced about 300 W of heat.

Following nondestructive testing (i.e., ultrasonic bond inspection and a helium leak test) to establish the integrity of the container welds and bonds, each disposal container is loaded into a shielding container cask. Each full cask is transferred to the disposal vault using the conveyance in a dedicated waste shaft. When removed from the conveyance, the cask is moved by crane to an underground storage area or by truck directly to a disposal room.

In this conceptual design, each disposal room is excavated by careful blasting and is about 8 m wide, 5 to 5.5 m high and 230 m long. Up to 282 vertical emplacement boreholes are drilled *in the floor* of each disposal room, and each borehole is prepared to receive a disposal container. The emplacement boreholes are 1.24 m in diameter, and 5 m deep, and are spaced about 2.1 m apart on centre, three across the room and 94 along the room, as required to keep the maximum temperature of the container shell below 100°C. Before a container cask is received in the disposal room, fractures that are seeping groundwater into the disposal room or emplacement borehole are sealed with either clay-based or cement-based grouts. A clay-based buffer material (i.e., 50% sodium-bentonite clay and 50% silica sand by dry mass at 17% to 19% moisture content) is compacted in layers into the emplacement borehole to a dry density of ≥167 Mg/m^3 (95% of the dry density attainable in ASTM test D-1557-78 (9)). A hole is augered centrally into the buffer to receive the container. When the container has been emplaced, the annular gap between the container and the buffer is filled with dry silica sand to improve heat transfer and to maintain buffer density. Additional buffer material is then placed and compacted over the container to the floor level of the disposal room.

When all the emplacement boreholes in a room have been filled, the room is backfilled by placing and compacting a mixture of 25% glacial-lake clay and 75% crushed granite, by dry mass, at 6% to 8% moisture content to a dry density of 2.1 Mg/m^3 to fill the lower 3.5 m of the room. This lower backfill is spread and compacted in layers using low-profile loaders, spreaders and roller compactors. The upper portion of the room is filled by spray-compacting into place (e.g., with modified shotcrete application equipment) an upper backfill material similar in composition to the buffer material. A concrete bulkhead is constructed at and grouted into the room entrance to withstand the buffer and backfill swelling and the groundwater pressures. All underground transportation of the clay-based and cement-based sealing materials is done using modified diesel-powered underground trucks with 18 m^3 rotating, mixing drums. A safeguards seal may be incorporated into the bulkhead to detect unauthorized entry.

The operational sequence, consisting of disposal room excavation by the drill-and-blast method, emplacement-borehole drilling and preparation, waste emplacement, borehole sealing and room backfilling and sealing, continues throughout the operating period of the disposal vault. The disposal rooms are developed and filled in sequence, retreating from the upcast ventilation shaft complex toward the service shaft complex to control access, potential contamination, and potential radiation doses to personnel.

When the vault has been filled with waste, the monitoring data have been assessed to show compliance with the regulatory and design criteria, and the regulators have approved the decommissioning and closure plan for the disposal centre, the access tunnels, service areas and shafts are backfilled and sealed. The materials and methods for backfilling the tunnels and service areas are similar to those used in the disposal rooms. The backfill in the shafts is the lower backfill material compacted into place using vibrating or roller compactors suspended for the working platforms. At strategic locations in the tunnels and shafts, such as on each side of fracture zones, concrete bulkheads and gasket seals are installed. The gasket seal is a plug constructed of highly compacted bentonite clay blocks on the side of each bulkhead that is away from the fracture zone. At this time, the surface facilities are decommissioned and disassembled, and the surface of the site is permanently marked and is returned to a state suitable for public use.

Thermal-mechanical Analysis

Thermal, mechanical and coupled thermal-mechanical analyses were done for the disposal rooms and emplacement boreholes. An analytical code was used initially to analyze the temperature distribution for a vault at a depth of 1000 m to select the borehole-to-borehole spacing that satisfied the 100°C maximum temperature limit.

The stability of the disposal room was analyzed using the finite-element method for excavation (ambient temperature) conditions and for sealed (heated) conditions. Two cases were analyzed for the average in situ stress conditions assumed at a depth of 1000 m in the Canadian Shield with rooms excavated in the conservative direction perpendicular to the maximum horizontal stress direction:

1. a disposal room with a flat floor and with boreholes spaced at 2.1 m across and along the room, and
2. a disposal room with a curved floor similar to the crown of the room and with boreholes spaced at 2.1 m across and 3.0 m along the room.

In both cases, the analyses of the excavation condition indicated zones of yielding in the floor of the disposal room and along the emplacement borehole walls. These zones were judged to be larger than desired based on the Underground Research Laboratory studies of rock response to excavation (e.g., (10)). Therefore, a similar analysis was done for the in situ stress conditions assumed at a depth of 500 m and a borehole spacing of 2.1 m across and along the room. The results indicated that the stability of the room and borehole excavation boundaries would be acceptable.

This specific borehole emplacement configuration array, for the assumed in situ stress, room orientation and rock strength (or failure) criteria, is suitable only for depths shallower than 1000 m. The in-room emplacement configuration may be preferable for abnormally high in situ stress conditions found in the Canadian Shield, or for depths greater than 500 m under average stress conditions for lower strength rock.

A limit equilibrium analysis was done using stress information from a finite-element analysis to assess the potential for shear displacement on a subhorizontal and a subvertical fault zone near a sealed disposal vault at a depth of 1000 m. No shear displacements are expected below a depth of 100 m from the ground surface.

Resource Requirements

The cost of a disposal facility will be sensitive to changes in a wide range of parameters. Examples of the sensitivity of the disposal facility schedule and nominal costs to the quantity of used fuel to be disposed and to the depth of disposal are shown in Table I.

The cost for the specific disposal centre to dispose of 10.1 million used-fuel bundles at a depth of 1000 m is estimated to be about $13.32 billion from the beginning of the siting stage through to the end of the closure stage, a period of 89 a. It would provide about 62 200 person-years of direct on-site employment.

It is judged that the nominal estimates presented may be as much as 15% high or 40% low. These cost estimates could change significantly for a disposal facility if different engineered barriers are selected or if the disposal vault

TABLE I
Nominal Cost Estimates for
a Single-Level Disposal Vault Using In-Floor
Borehole Emplacement

Disposal Vault Capacity (million bundles)	Depth (m)	Project Duraction (years)	Nominal Estimated Cost (1991) Canadian $million)
10.1	500	86	13,110
10.1	1,000	89	13,320
7.5	1,000	76	10,950
5.0	1,000	63	8,680
Note: Data are from (1).			

arrangement becomes more complicated to account for local site conditions. The costs are given in constant 1991 Canadian dollars excluding any financing costs.

A SINGLE-LEVEL USED-FUEL VAULT USING THE IN-ROOM EMPLACEMENT CONFIGURATION

A single-level room-and-pillar disposal vault using the in-room emplacement configuration is expected to be more suited for the stress conditions that may be encountered in the plutonic rocks of the Canadian Shield at a depth greater than about 500 m. A conceptual design study is being done by AECL to assess the features of in-room emplacement. As the study is in progress there is a limited amount of information available at the time of writing.

Study Specifications

The specifications for this study are in many ways identical to the in-floor borehole emplacement study discussed above. The major exceptions are:

1. The capacity of the disposal vault will be determined by maintaining the waste emplacement area at about 2 km by 2 km and the required container-to-container and room-to-room spacing to satisfy the temperature criteria.
2. The disposal vault will be a single-level room-and-pillar arrangement using the in-room emplacement configuration suited for application at 1000 m depth in the plutonic rock of the Canadian Shield.
3. The in situ stress conditions assumed will be consistent with the upper range of data now available for the stress conditions in the Canadian Shield.
4. The disposal container will be a packed particulate container fabricated from 25.4 mm thick copper, which holds 72 used-fuel bundles. The disposal container is 1177 mm high and 860 mm in diameter with a minimum thickness of 25 mm. The mass of a full container is 3.4 Mg.
5. The failure criteria for acceptability of the disposal room arrangement will be that there should be no locations around the room with an indicated strength-to-stress ratio of less than 1 under excavation conditions where strength is defined using the Hoek-Brown empirical failure criteria.
6. The minimum buffer thickness around each disposal container will be 0.5 m.
7. The temperature limit on the buffer material and the other surface of the disposal container will be 90°C for moist buffer and 100°C for dry buffer, using the appropriate thermal properties for each material.
8. Limited quantities of concrete may be used between the clay-based buffer material and the rock of the excavation.

Facility Description

The surface facilities at this disposal centre are identical to those of the in-floor borehole emplacement disposal centre except for the container and basket fabrication and the packaging plant. Some modifications are being made to the concepts for these facilities to accommodate the copper container design and geometry.

Based on work done, it appears that the disposal room may be about 6 m wide and 3 m high in the shape of an ellipse to accommodate the stress conditions assumed at a depth of 1000 m (Fig. 4). The scoping thermal (analytical) and mechanical (boundary element) analyses indicated that two disposal containers could be placed across the room spaced at 1.4 m apart on centre and each pair of containers could be spaced at 4.6 m on centre along the room. The final dimensions will be established over the next few months by three-dimensional thermal-mechanical finite-element analyses.

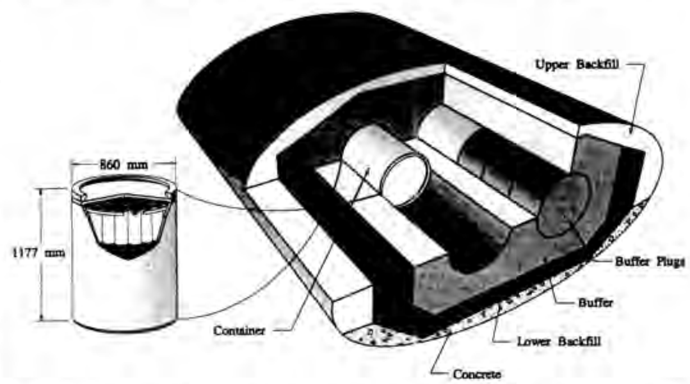

Fig. 4. Disposal room showing the in-room emplacement of disposal containers.

We anticipate that this conceptual design will have a concrete floor in each disposal room for anchoring track and accurate locating of equipment. The placement of the buffer material, the backfill material and the disposal containers will be done using track-mounted equipment to facilitate container and buffer placement. The lower backfill, having a composition similar to that described above but with the addition of up to 5% sodium-bentonite clay (to improve block fabrication), will be formed into precompacted blocks for placement on the concrete floor. The buffer material, similar in composition to that discussed above, will be formed into precompacted blocks and placed on the lower backfill. The buffer blocks will be designed with the cavity shaped to receive containers and which will provide the necessary shielding once a pair of containers is completely covered. The backfill and buffer blocks will be placed using remotely operated equipment. When the placement of the buffer blocks around a pair of disposal containers is completed, the radiation fields in the disposal room will be low, allowing personnel to enter the room.

The space between the buffer/container assemblage and the room boundaries will be filled with the upper backfill, placed using a pneumatic-compaction method.

As the thermal-mechanical analyses are done and concepts for each of the operations are developed, the details of this conceptual design may change. It is anticipated that this disposal vault arrangement using the in-room emplacement configuration will be suitable for higher stress conditions than a vault using the borehole emplacement configuration since the excavation geometry is simpler with fewer irregularities to create local stress concentrations.

The resource requirements and disposal centre schedules will be prepared later in the study.

SUMMARY

The feasibility and practicability of nuclear fuel waste disposal are important issues in the CNFWMP. These issues are being addressed through a series of scoping and conceptual design studies of disposal facilities that provide information for assessing the advantages and disadvantages of various disposal vault arrangements, waste emplacement configurations and sealing system application methods in the context of disposal in the plutonic rock of the Canadian Shield.

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