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DEEP GEOLOGIC REPOSITORY CONCEPTS FOR ISOLATION OF USED FUEL IN CANADA

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ABSTRACT

The concept of a deep geologic repository (DGR) for long-term management of CANDU® reactor used fuel within the stable plutonic rock of the Canadian Shield was developed by Atomic Energy of Canada Limited (AECL) between 1978 and 1996. Since 1996, Ontario Power Generation (OPG), formerly Ontario Hydro, has been leading the development of a modified DGR concept, taking into account the 1998 recommendations of the federal Environmental Assessment and Review Panel. This paper discusses progress to date in the development of modified DGR conceptual designs and technologies.

I. INTRODUCTION

In Canada, used nuclear fuel is stored in water-filled pools and, after about ten years out-of-reactor, in steel-lined concrete dry storage containers at the nuclear reactor sites. These storage practices, while safe, require continuous institutional controls, such as security measures, monitoring and maintenance. In 1978, the governments of Canada and Ontario established the Canadian Nuclear Fuel Waste Management Program as a step towards developing a long-term solution to the management of used nuclear fuel. Atomic Energy of Canada Limited (AECL) and Ontario Hydro (now Ontario Power Generation Inc. (OPG)) have advanced the concept for emplacing used nuclear fuel in a DGR within the stable plutonic rock of the Canadian Shield[1]. Based on the recommendations of a federal Environmental Assessment and Review Panel[2], geologic disposal on the Canadian Shield is one of the approaches that the Government of Canada has identified for further consideration in the *Nuclear Fuel Waste Act*, which was passed in parliament in June 2002 and brought into force on November 15, 2002. OPG and the other Canadian nuclear fuel waste owners have formed the Nuclear Waste Management Organisation (NWMO) to study and assess approaches for long-term management of used nuclear fuel and to recommend an approach to the Government of Canada in late 2005. In addition, OPG is continuing to develop DGR technology and is maintaining sufficient technical expertise to initiate a siting program for a DGR, should the federal government select this approach. Russell and Simmons[3] summarized developments in Canadian DGR concepts to 2002. A specific updated DGR design concept was prepared for NWMO by used-fuel owners[4]. This paper discusses progress to date in the development of modified DGR conceptual designs and technologies.

II. DEEP GEOLOGIC REPOSITORY CONCEPT

The Canadian DGR concept comprises a system of multiple engineered barriers that include the waste form (i.e., currently used CANDU® reactor fuel bundles), container, repository sealing systems and the geosphere[1]. The repository concept entails encapsulating bundles of used fuel in durable containers and sealing the containers in a repository located at a depth of between 500 to 1000 m in the stable plutonic rock of the Canadian Shield, Sedimentary rock may also be a suitable DGR host medium and is being studied in other countries (e.g., France, Switzerland). An illustration of the current DGR conceptual design under consideration in Canada is shown in Figure 1. The schematic representations for container emplacement options are shown in Figure 2.

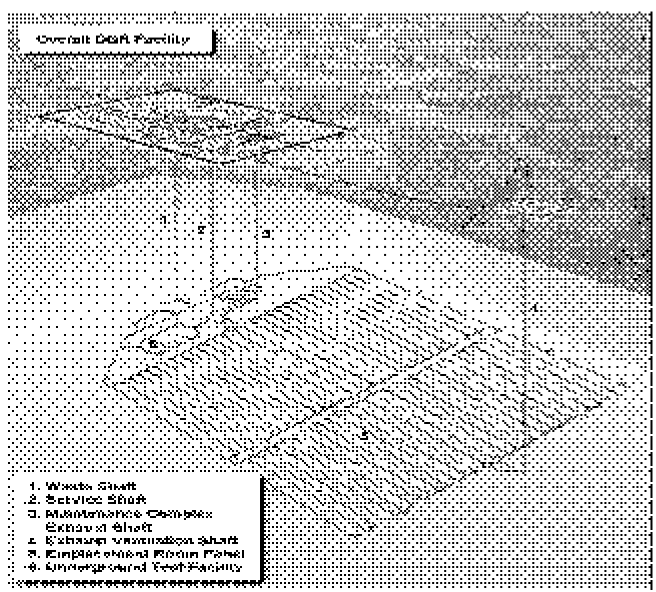

Figure 1: Illustration of the Updated Canadian DGR Conceptual Design

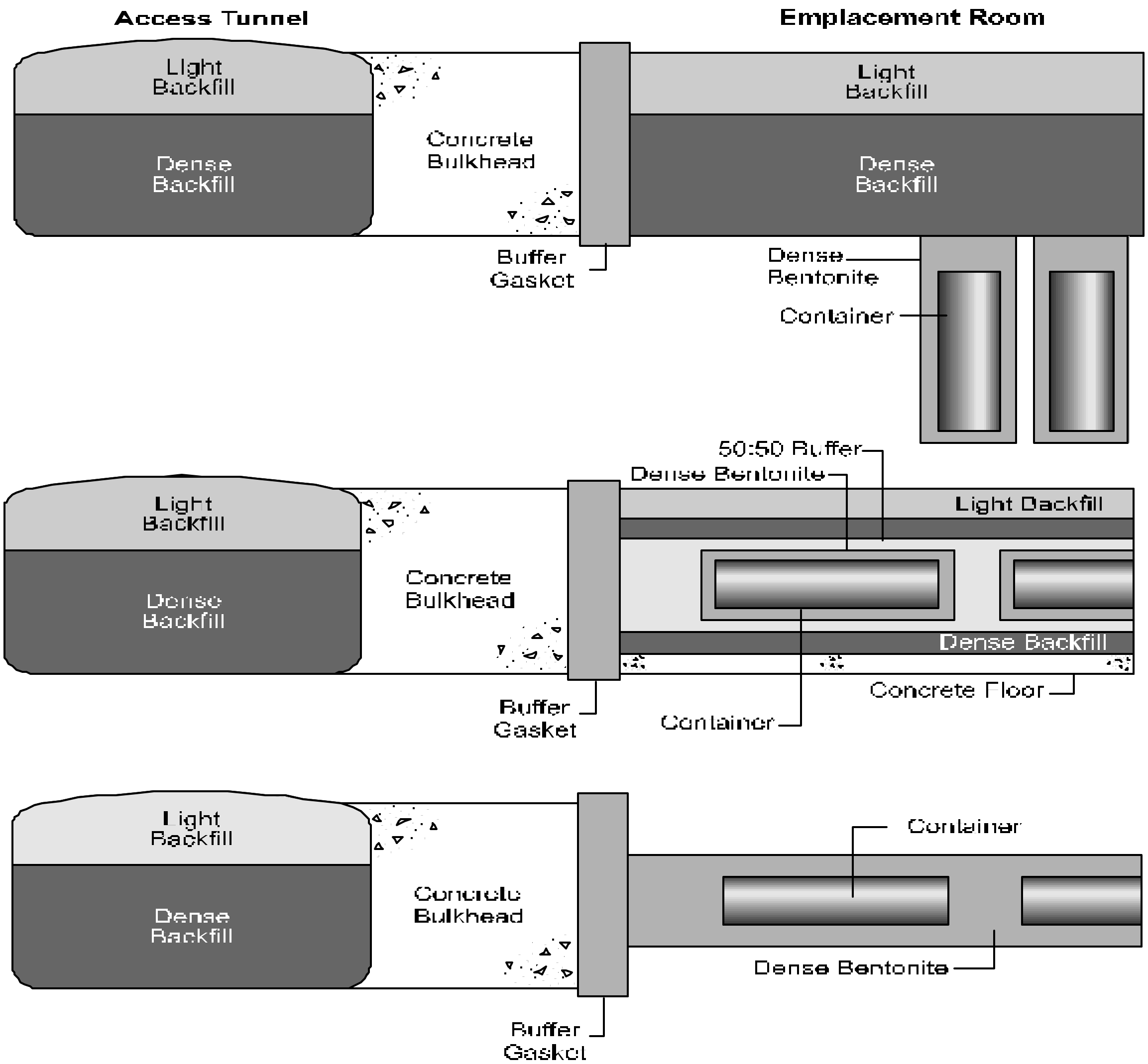

Figure 2: Schematic representations of container emplacement options (not to scale): in-floor borehole, in-room and horizontal borehole (from top to bottom)

The repository would be a network of horizontal tunnels and emplacement rooms designed to suit the rock structure, groundwater flow and other subsurface conditions at the particular site. Particular characteristics of relevant rock masses in the Canadian Shield that favour a DGR include: low permeability rock with sparse fracturing; old, saline groundwater; small gradients to drive groundwater movement; no economic mineralization; and reducing groundwater and porewater conditions. The containers would be placed either within the rooms or in boreholes drilled from the rooms. Clay-based sealing materials would surround the used-fuel containers and would completely fill all remaining voids in each emplacement room to ensure low-permeability and chemically and biologically benign conditions.

After all emplacement rooms are filled and sealed, there would be a suitable period of monitoring to confirm that the facility is performing as expected. During this period, the repository and surrounding rock mass would be heated and the unsaturated portions of the system would begin to saturate. After a sufficient period of post-operational monitoring, and in consultation with stakeholders, all remaining tunnels, shafts, service areas and exploration boreholes would be backfilled and sealed such that long-term safety of the facility would not depend on institutional control. The repository concept includes extended monitoring of the repository and the option of retrieving the used fuel containers, if required.

III. USED-FUEL CONTAINER

OPG's studies have led to the development of an updated long-lived and robust used-fuel container (UFC) design[5]. The preliminary used-fuel container requirements[6] specify a container design life of not less than 100,000 years under conditions expected within the 500 to 1000 m depth range in the plutonic rock in the Canadian Shield (i.e., including the effects of future continental glaciation). A screening study was carried out by OPG to select a limited number of preferred UFC geometries and used-fuel bundle capacities[18]. A total of 16 UFC designs with capacities ranging from 72 to 360 fuel bundles were evaluated. From this screening study, four UFC geometric designs, having capacities of 288 to 324 bundles, were recommended as preferred designs for future safety and engineering studies since they have lower estimated costs than other container geometric designs, and lower annual container throughput rate than the 72-bundle container conceptual design described in the Environmental Impact Statement (EIS) Case Study[1]. A UFC design with a capacity of 324 bundles has been selected as the reference for the updated DGR conceptual design since it has the largest container fuel capacity among the four recommended UFC geometric designs and its size and geometry are similar to the Swedish used-fuel container design.

The currently projected number of used-fuel bundles that will arise in Canada is about 3.6 million. With an assumed operation period of 30 years, the reference container emplacement rate in a DGR would be about 370 containers per year, which would be comparable to 60 and 200 containers assumed per year in the Finnish and Swedish waste management programs, respectively.

The reference UFC design consists of an outer copper corrosion barrier vessel and an inner steel load-bearing vessel (Figure 3). The container design is robust in terms of long-term corrosion resistance and mechanical stability. OPG has chosen oxygen-free phosphorus-doped copper (OFP-Cu) as the primary corrosion-barrier vessel material[7]. Corrosion studies to date have supported the prediction that the OFP-Cu corrosion-barrier vessel would have a corrosion service life of more than 10^6 years under expected repository conditions[8]. OPG has been developing corrosion models for predicting general corrosion and localized corrosion (microbiologically-influenced corrosion, under-deposit corrosion and stress corrosion cracking) behaviour of copper vessels in a hypothetical Canadian DGR[9, 10, 11]. OPG has also been carrying laboratory experiments to improve the understanding of the localized corrosion mechanisms [11, 12, 13, 14]. Internationally, relevant longer-duration in-situ corrosion experiments that include either copper specimens or full-scale copper vessels are being carried out in Sweden to evaluate copper corrosion under granitic bedrock conditions[15, 16].

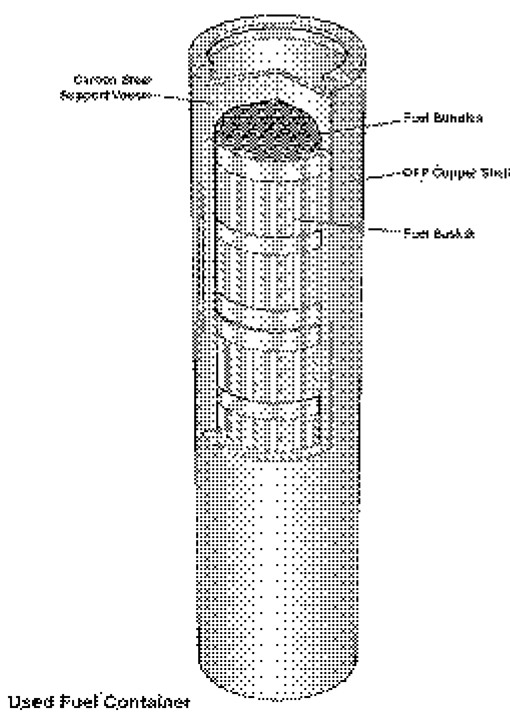

Figure 3: Cut–away View of the Reference Used-fuel Container[4]

An steel inner vessel and a cast iron insert were assessed and compared as the inner load-bearing component of a UFC[17]. The inner steel vessel has been recommended as the load-bearing component of the reference UFC primarily because feedback from manufacturers indicated that:

- the fabrication and inspection of the cast iron insert are uncertain primarily because of the large number of fuel-bundle channels in the casting (36 to 60 channels); and
- inner vessels of a wide range of geometry and size can be readily fabricated using existing technology.

IV EMPLACEMENT ROOM SEALING SYSTEMS

OPG is developing preliminary design requirements for: the emplacement room sealing system; the bulkhead sealing system; the tunnel, service-area, shaft and ramp sealing system; and the borehole sealing system. Each preliminary design requirement includes functional and performance requirements related to permeability, microbial viability, chemistry, contact pressure and design life. These are discussed generally in [19].

OPG's development work has focussed on the emplacement room and the bulkhead sealing systems with particular emphasis on: excavation of stable openings in sparsely fractured, highly stressed rock; control of the excavation damage zone in the near-field rock; monitoring and modelling of the clay-based materials performance; and limiting the viability and mobility of micro-organisms in the sealing materials adjacent to the container.

A dense bentonite component surrounding each UFC has been included in the updated DGR conceptual design to minimize the microbial activity adjacent to the containers. Microbial experiments in the Swedish program have indicated that the extent of microbial activity adjacent to a container would be severely limited in 100% bentonite material with a water-saturated density of 2 Mg/m^3 [20]. This water-saturated bentonite would develop a swelling pressure in the order of about 5 MPa and a water activity of less than 0.96 in groundwater.

Preliminary analyses[21] have been performance on the emplacement configurations shown in Figure 1 assuming the component materials listed in Table 1 and the presence of gap fill material.

The analytical results for the in-floor borehole emplacement configuration suggest that the pressure at the container surface would be at least 2 MPa, the water activity would be <0.96 and the hydraulic conductivity requirements would be $<10^{-10}$ m/s, if the:

- dense bentonite EMDD (for definition see note Table 1) is at least 1.4 Mg/m^3; and
- dense bentonite/rock gap fill has an EMDD of >0.85 Mg/m^3.

The results for the in-room emplacement configuration suggest that the EMDD achievable with the light backfill specification in Table 1 is not adequate to constrain the expansion of the other sealing system components and therefore the pressure at the container surface would be less than 1.5 MPa. This light backfill specification is presently being reviewed. The performance of the buffer in the horizontal borehole configuration is expected to be similar to the buffer performance in the in-floor borehole configuration.

Table 1: Representative Composition and Properties of Sealing Materials in Current OPG Repository Sealing System Conceptual Designs[3]

Property	Dense Bentonite Buffer	50:50 Buffer	Gap Fill	Dense Backfill	Light Backfill	Concrete
Material Composition	100% bentonite	50% bentonite 50% sand	100% pelletised bentonite	5% bentonite 25% glacial clay 70% crushed granite aggregate	50% bentonite 50% sand	low-heat high-performance concrete (LHHPC)
Initial Porosity (as placed)	0.41	0.38	0.49	0.22	0.55	0.15
Initial Saturation (% max)	65	80	6	80	33	50
Initial Moisture (water mass/dry mass) (%)	17	18.5	2	8.5	15	3
Maximum Moisture (water mass/dry mass) (%)	26	23	36	10.6	46	6
Thermal Conductivity (W/m?K)	0.5 (dry) 1.0 (as placed) 1.2 (saturated)	0.7 (dry) 1.7 (as placed) 1.7 (saturated)	0.5 (dry) 0.5 (as placed) 1.2 (saturated)	1.0 (dry) 2.0 (as placed) 2.0 (saturated)	0.5 (dry) 0.7 (as placed) 1.4 (saturated)	1.85
Heat Capacity (J/kg?K)	880 (dry) 1440 (as placed) 1520 (saturated)	870 (dry) 1350 (as placed) 1460 (saturated)	890 (dry) 910 (as placed) 1710 (saturated)	860 (dry) 1100 (as placed) 1160 (saturated)	900 (dry) 1280 (as placed) 1870 (saturated)	900
Density (kg/m^3)	1610 (dry) 1950 (as placed) 2010 (saturated)	1690 (dry) 1980 (as placed) 2060 (saturated)	1400 (dry) 1410 (as placed) 1880 (saturated)	2120 (dry) 2280 (as placed) 2330 (saturated)	1240 (dry) 1400 (as placed) 1780 (saturated)	2430
EMDD+ (kg/m^3)	1500	1150	1250	800	1000	-
Saturated Hydraulic Conductivity (m/s) (assuming 100 g/L saline)	5.0×10^{-13}	1.0×10^{-10}	1.0×10^{-11}	2.0×10^{-11}	1.0×10^{-9}	1.0×10^{-12}

+ EMDD - Effective Montmorillonite Dry Density = (mass of bentonite *montmorillonite fraction) / (volume of voids + volume of montmorillonite minerals) – assumes that bentonite is 75% montmorillonite content

A study of backfill materials and technologies[22] has also been completed that considered the placement of dense and light backfill in large openings as precompacted blocks, by in-situ compaction and by pneumatic placement, and for smaller openings (e.g., gaps) by gravity pouring and low-pressure pneumatic placement. The study concluded that:

- gap fills could be placed in confined spaces as dry free-flowing materials using pouring or low-velocity pneumatic placement methods and that gap fills comprising bentonite pellets with an EMDD of ~2 Mg/m^3 could be placed to an EMDD of between 0.8 to 1.4 Mg/m^3; and

- dense backfill would likely be a mixture of glacial lake clay and crushed rock placed as precompacted blocks or compacted in-situ in lifts of 200 mm or less.

Multi-year studies are underway to examine the effect of bentonite properties (density, swelling pressure, and water activity) and water salinity on the extent of microbial activity in saturated dense bentonite material, and to improve the as-placed density and EMDD of light backfill and gap-fill materials.

V REPOSITORY DESIGN STUDIES

Updated conceptual DGR designs have been developed based on the UFC design with a capacity of 324 fuel bundles for the in-room, in-floor borehole and horizontal borehole container emplacement configurations. The design parameters for the updated DGR designs and the previous AECL-developed DGR concepts are shown and compared in Table 2. The schematic representations of the updated container emplacement options are shown in Figure 2. In these updated designs, the UFC is surrounded by a dense bentonite. Analytical and numerical analyses have shown that thermally and structurally acceptable underground repository layouts can be designed for all three container emplacement configurations. A specific updated in-room DGR design concept was developed and prepared for the NWMO by the used-fuel owners[4]. This DGR conceptual design study addressed the feasibility and method of implementing the conceptual design, the cost of the implementation and the feasibility of container retrieval.

Table 2: Comparison of Design Parameters-
Two Previous AECL Case Studies and Updated DGR Conceptual Designs

Parameter	AECL's In-Floor Borehole Emplacement Configuration Case Study [24]	AECL's In-Room Emplacement Configuration Case Study [25]	Updated DGR Conceptual Designs
Quantity of waste (CANDU® fuel bundles)	10 100 000	5 800 000	3 600 000
Number of Used Fuel Containers	140 256	80 556	11 112
Disposal rate (fuel bundles/a)	250 000	250 000	120 000
Duration of the Operation Stage (a)	41	23	30
Approximate overall waste emplacement area (km^2)	4	4	1.9 - 2.2
Used fuel burnup (GJ/kg U / MWh/kg U)	684 / 190	720 / 200	790 / 220 (mean) 1008 / 280 (95th percentile)
Minimum cooling time at disposal (a)	10	10	30
Maximum container outer surface temperature (°C)	100	90	100
Container	Ti-shell, particulate-packed 633-mm diameter, 2246-mm long.	Copper shell, particulate-packed 860-mm diameter, 1189-mm long.	Copper shell, inner steel vessel 1168 mm diameter, 3867 mm long
Container capacity (bundles)	72	72	324
Emplacement depth (m)	1000	750	1000
Container emplacement	In-floor borehole emplacement: vertical, single UFC	In-room emplacement: horizontal, two UFCs abreast	In-floor borehole emplacement: vertical, single UFC In-room emplacement: horizontal, one or two UFCs abreast Horizontal borehole emplacement: horizontal, single UFC
UFC Emplacement room/borehole seals	• In-situ compacted 50:50 bentonite/sand buffer immediately surrounding the UFC • In-situ compacted dense backfill • Pneumatically placed light backfill	• Precompacted 50:50 bentonite/sand buffer blocks immediately surrounding the UFC • Precompacted dense backfill blocks of crushed granite, glacial lake clay and bentonite • Pneumatically placed bentonite-based light backfill	• Precompacted bentointe buffer blocks immediately surrounding the UFC • Precompacted 50:50 bentonite/sand outer buffer blocks (in-room concept only) • Dense and light backfill (in-room and in-floor borehole concepts) (see Figure 2 for details)

VI MONITORING

OPG is taking a broad approach to addressing the issue of long-term monitoring in a geologic repository by: documenting the state-of-the-art in instrumentation; identifying gaps in current instrumentation and in the application of these instruments to long-term monitoring; and developing an approach to long-term repository monitoring. A recent study[23] discusses international approaches to long-term monitoring, describes the technologies available for application in a long-term monitoring program, and describes in a possible strategy for the long-term monitoring of a DGR beginning with facility siting and continuing through repository operation, extended underground monitoring, decommissioning and closure. Component and demonstration testing is proposed that would take place during the repository operation and extended underground monitoring stages. Because the installation of monitoring systems within the waste emplacement rooms could jeopardize long-term safety, the study recommends the use of demonstration tests that include placement of used-fuel containers in a simulated emplacement room, with extensive instrumentation and monitoring for an extended period prior to decommissioning and closure.

The proposed schedule involves partial decommissioning of the repository system to allow additional time for underground monitoring, with eventual transfer to permanent passively safe isolation when the entire repository is closed. When a final decision is made to permanently close the repository, extended monitoring using surface-based systems may continue consistent with the requirements set by stakeholders at that time. The proposed monitoring program should not jeopardize the long-term, passive safety of the DGR.

VII RETRIEVAL

The retrieval of waste containers from a repository has been considered at the conceptual level for both in-floor borehole and in-room emplacement configurations using the 72-bundle used-fuel container in the EIS and second case studies[24, 25] and the updated in-room emplacement configuration with the current reference 324-bundle used-fuel container[4]. The general conclusion of these studies is that retrieval would be feasible but specific methods and equipment would have to be developed and demonstrated. Used-fuel container retrieval tests are being carried out at the Äspö Hard Rock Laboratory in Sweden to demonstrate one approach to recovering emplaced containers when the surrounding dense bentonite is fully saturated and has reached its maximum swelling pressure [16].

VIII SUMMARY

Modified deep geologic repository (DGR) and used-fuel container (UFC) conceptual designs have been developed taking into account the 1998 recommendations of the federal Environmental Assessment and Review Panel. A robust long-lived reference UFC design has been developed, which has an outer copper corrosion-barrier vessel, an inner steel load-bearing vessel and a large container fuel capacity. Significant developments in the DGR conceptual design include the ongoing development of the preliminary design requirements for the sealing systems, the inclusion of dense bentonite buffer immediately around the UFC to minimize microbial activity for container longevity, the realization of the deficiencies in the light backfill and gap fill material performance and possible solutions, and the confirmation of the feasibility of container retrieval. In addition, an approach to long-term repository monitoring has been described.

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