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TECHNICAL IMPLICATIONS OF AGING USED FUEL PRIOR TO DISPOSAL WITHIN A DEEP GEOLOGIC REPOSITORY

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ABSTRACT

Delaying the disposal of used CANDU® fuel can reduce the plan area and excavated volume of a deep geologic repository, and therefore the cost, because the decreased thermal power from radioactive decay would allow containers to be placed closer together. Potential negative effects of reducing the repository size include the increase in duration of elevated long-term temperatures for the used-fuel containers and the decreased structural stability of the excavations from the increased long-term thermal load. First, the factors affecting repository cost as a function of heat distribution and heat transfer are presented. Then the potential negative effects are discussed.

I. INTRODUCTION

The deep geologic repository (DGR) concept for the disposal of used CANDU® fuel involves emplacing heat-generating, used-fuel containers at a depth ranging between 500 to 1000 m in a plutonic rock mass.[1] A number of waste emplacement configurations are being considered including variations of the borehole-emplacement and in-room-emplacement methods.

In the Canadian concept, the post-reactor discharge age of used fuel would be at least 30 years at the time of emplacement.[1] This age is due to a number of factors, including the likely schedule for start of emplacement, assuming that there is a decision to proceed with siting and construction of a deep geologic repository.

Further delaying used-fuel disposal results in further decay of the radioactivity, in turn, reducing the intensity of the heat source of and gamma flux from the waste. This delay affects repository design decisions regarding the temperature of the container and surrounding sealing materials and rock, the structural stability of the emplacement rooms and the radiological shielding requirements for the protection of repository operators. The coupled thermal-mechanical behaviour of the rock complicates the analysis. For example, an increase in the average temperature throughout the DGR will increase the thermal expansionary stresses in the horizontal direction and to a lesser extent in the vertical direction.[2,3] This increase in stress and stress ratios can decrease the structural stability of the waste emplacement room, depending on the specifics of the room design.

First, the factors affecting repository cost as a function of heat distribution and heat transfer are presented. Then the effects of the duration of elevated temperatures on the structural stability of excavations and on used-fuel containers and sealing materials are discussed. The analysis is presented for the horizontal borehole emplacement concept. This concept is based on SKB's KBS-3H waste emplacement method, as applied to Canadian conditions and used-fuel container

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(Figure 1).[4] The conclusions are anticipated to be similar for other waste-emplacement methods.

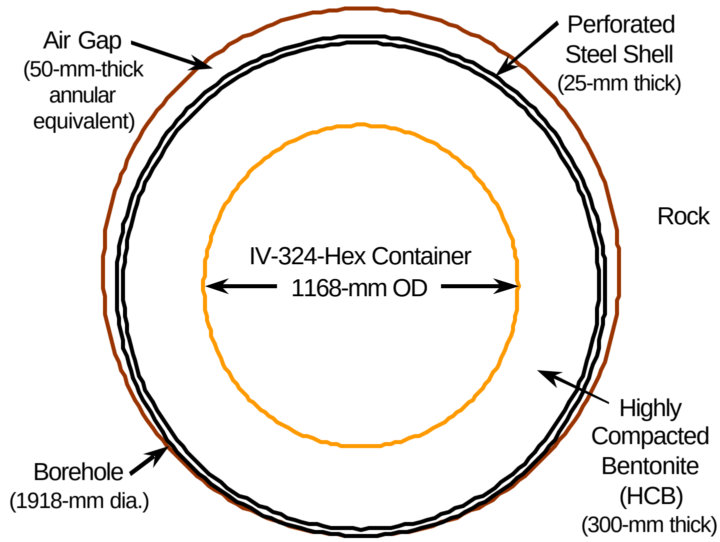

Figure 1: Cross-sectional view of horizontal borehole emplacement arrangement and dimensions with reference Canadian used-fuel container concept.

II. THERMAL DESIGN

Thermal Source Term

The primary heat-generating radionuclides in used fuel beyond 10 years from reactor discharge are the short-lived fission products (e.g., predominantly ^{137}Cs and ^{90}Sr and their decay products) and the long-lived actinides (e.g., predominantly ^{241}Am, ^{240}Pu, ^{239}Pu). The crossover point where the heat output from fission products equals that of the actinides is about 80 years for used CANDU fuel with average burnup (Figure 2).

The reference used-fuel container is the IV-324-hex design, consisting of 324, 37-element, used-fuel bundles at an average burnup of 220 MWh/kg U in an 1168-mm diameter and 3867-mm long package.[1,5] Figure 2 provides the heat generation rate of the container as a function of the post-reactor discharge age. For example, the container heat output is about 1140 W at 30 years and 960 W at 40 years.

Waste Emplacement Configuration

For the following analyses, the wastes are emplaced in horizontal boreholes. This is similar to SKB's KBS-3H waste emplacement method and is applied to Canadian Shield conditions at a depth of 1000 m and the IV-324-hex used-fuel container.[4] The emplacement rooms are long (~300 m), large-diameter horizontally drilled boreholes. In this design concept, highly compacted bentonite (HCB), 0.3-m thick, is pre-packaged around the IV-324-hex used-fuel container and is held in place with a perforated steel shell. The entire container with the HCB and perforated shell is installed as one assembly in a 1.918-m diameter borehole (Figure 1).

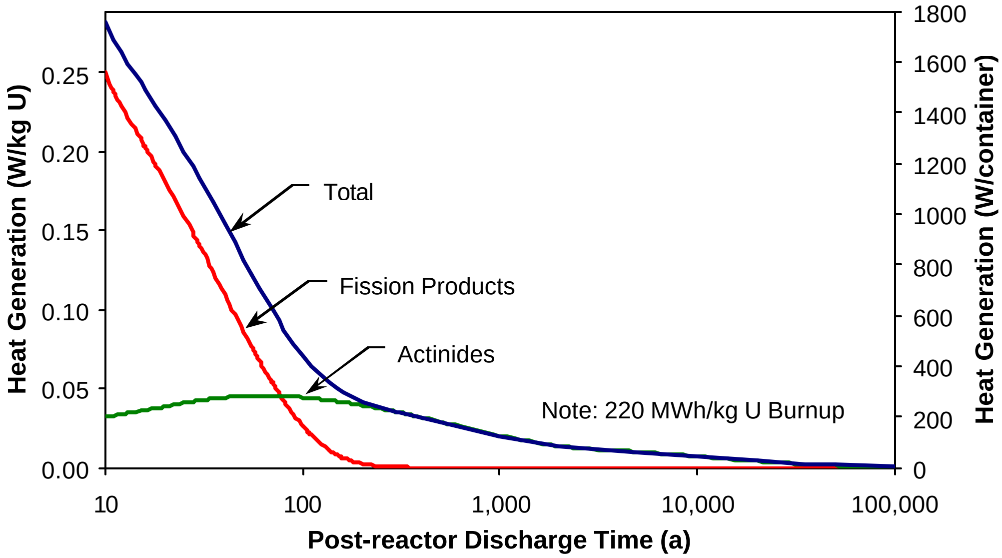

Figure 2: Radiogenic heat output of used CANDU® fuel.[after 5]

The clearance gap between the container assembly and borehole perimeter is needed for assembly installation and is not subsequently filled by any sealing material in this conservative thermal analysis. The HCB is expected to extrude through the perforated shell as it saturates to ultimately fill this clearance gap at a suitable swelling pressure and hydraulic conductivity. Since this is unlikely to occur within the time that the first temperature peak is reached in sparsely fractured granite, the conservative approach is to treat this unfilled "air" gap as a 50-mm thick annulus in the thermal analyses.

Thermal Analyses

The repository is assumed to contain 3.6 million used-fuel bundles at a depth of 1000 m at an ambient temperature of 17°C in granite. The assumed ambient surface temperature is 5°C and the thermal properties for the granite are provided in Table 1.

Table 1: Initial Material Properties

Parameters	HCB 1	HCB 2	HCB 3	Steel	Air	Granite
Thickness (m)	0.1	0.1	0.1	0.0127	0.05	NA*
Thermal Conductivity (unsaturated/saturated) (W/(m·°C))	0.45/1.3	0.85/1.3	1.25/1.3	54	0.074	3
Dry Density (kg/m^3)	1,600	1,600	1,600	7,833	1	2,650
Initial Water Content (%)	15%	15%	15%	NA	NA	<1%
Initial Bulk Density (kg/m^3)	1,840	1,840	1,840	7,833	NA	2,650
Initial Bulk Thermal Diffusivity (m^2/a)	NA	NA	NA	NA	NA	42.3

* NA – Not Applicable

These thermal analyses are performed with the HOTROK computer program, which provides an exact three-dimensional, transient-state, conductive heat-transfer solution for a large number of heat sources within a single material (i.e., granite) in a finite region of a semi-infinite half space.[6] Sealing materials are not initially included in the transient analyses but are added in a post-processing step. The thermal effect of the sealing materials is produced as a one-dimensional, steady-state heat transfer term for each material nested around the container that is then added to the initial transient solution in the post-processing step.[7] The resulting thermal approximation by adding the effect of sealing materials tends to be conservative by overestimating temperatures.[8] The effect of this steady-state superposition can be seen as an unusually high starting temperature at 0.01 years in Figure 3.

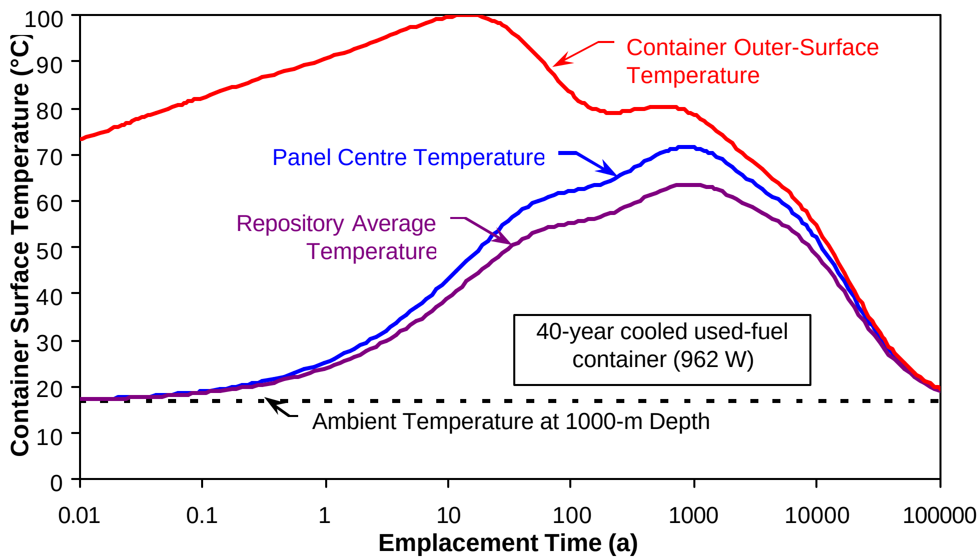

Figure 3: Temperature forecast of a repository with 40-year-old used fuel.
(a) Temperature at the outer surface of a container near the centre of a repository;
(b) Average rock temperature within a panel of rooms centrally located in a repository without any non-heating space for access tunnels, room bulkheads, etc.; and
(c) Average rock temperature based on fuel uniformly distributed or "smeared" throughout the repository plus all non-heating space including perimeter tunnels.

A design temperature limit is set for the outer surface of the container, based on ensuring optimum container and sealing system performance. In these analyses, this maximum design temperature is set at 100°C. The thermal properties of the sealing materials, perforated shell and air gap used in the analyses are provided in Table 1. Note that the 300-mm thick HCB is divided into three 100-mm thick annuli of differing thermal conductivity in order to approximate the effect of water redistribution expected due to drying in close proximity to the heated container during the early period of heating.

For a given age of fuel at the time of disposal, the spacings between the containers within an emplacement room and that between rooms are adjusted such that the maximum temperature on the outer surface of the container does not exceed 100°C. In general, there are several design options that meet the temperature limit for a given fuel age. Of the many possible solutions, the more economical container/room-spacing solution that meets prescribed constraints is selected based on the author's experience.

Thermal analyses of a container in a repository show a two-peak temperature response for 40-year-old used fuel (Figure 3). The rapid heating from the fission products within each container and its nearest neighbours and the insulating effect of the backfill "blanket" drives the first peak locally. This local temperature peak decays with fission-product decay but then increases to a second peak as the longer-term actinide decay heat builds up throughout the repository region and sustains itself for about 1000 years before beginning to decay back to near ambient temperature in about 100,000 years. Depending on the specifics of the repository design, the first peak temperature of the outer surface of the container occurs within 30 years.

Increasing the age of used-fuel decreases the heat output from the container. As a result, the spacing between containers within an emplacement room and the spacing between rooms can be reduced while meeting the maximum design temperature on the outer surface of the container. In turn, maximizing the emplacement density of the containers reduces construction costs and surface environmental impact by minimizing the excavated and backfilled volumes in the waste emplacement region of the DGR.

The estimated temperature responses for repositories that have been adjusted for different ages of used fuel are given in Figure 4. Table 2 provides some of the details for each predicted-temperature curve. Increasing the age of used fuel before emplacement decreases the temperature of the first peak relative to the second peak to the point beyond which the second peak controls the thermal design of the repository. For this horizontal-borehole example, the first-to-second peak transition occurs with 50-year-old used fuel. Current repository concepts are based on 30-year-old used fuel where the duration of the first temperature peak (e.g., >90°C) is relatively short (e.g., 25 a) and local to the container and some of the sealing system. The second peak temperature is well below the first peak. At an age of 50 years and greater, the duration of the second peak (e.g., >90°C) is in excess of 1400 years and the elevated temperatures extend well into the rock.

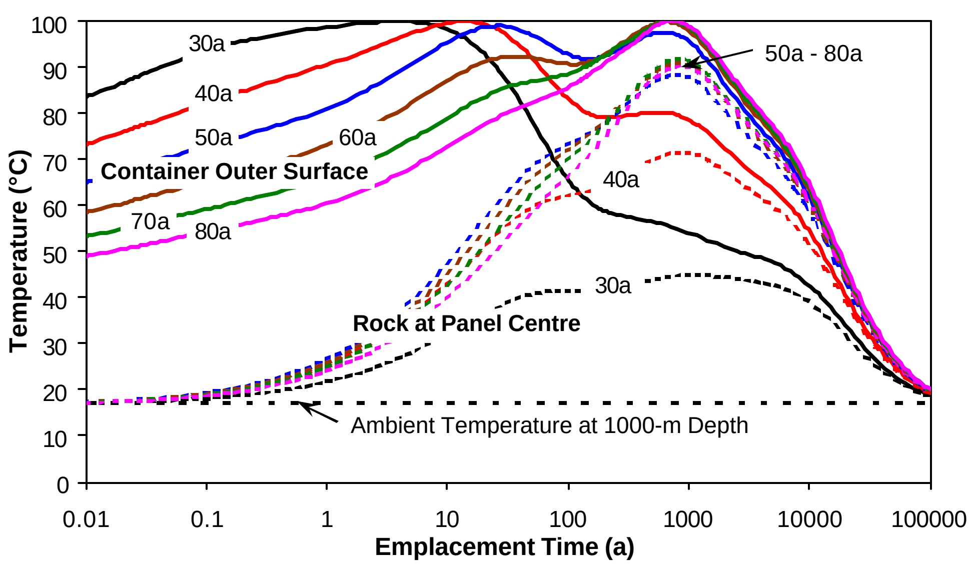

Figure 4: Temperature forecasts for repositories with used fuel of varying reactor discharge ages (solid lines are container outer surfaces, dashed lines are panel centres). Note: Container temperature curves for fuel age = 60 a are composites of unsaturated HCB (at first temperature peak <30 a) and saturated HCB (at second peak ~700 a) based on Table 2.

Table 2: Effect of Post-reactor Discharge Time for Used-Fuel on Repository Design

Used Fuel Discharge Age (a)	Room Spacing (m)	Container Spacing (m)	HCB[1] Thermal Conductivity (W/(m·°C))			IPTL[2] (W/m^2)	Repository				IGTL[3] (W/m^2)
			Layer 1	Layer 2	Layer 3		Width (km)	Length (km)	Area (km^2)	Volume (Mm^3)	
30	20.0	12.70	0.45	0.85	1.25	4.46	1.90	1.66	3.14	1.02	3.98
40	20.0	6.24	0.45	0.85	1.25	9.07	1.30	1.22	1.58	0.54	7.81
50	15.0	5.98	0.45	0.85	1.25	12.62	1.30	0.89	1.15	0.49	10.80
60	15.0	5.62	0.45/1.3	0.45/1.3	0.45/1.3	13.43	1.30	0.86	1.11	0.47	11.45
70	15.0	5.58	0.45/1.3	0.45/1.3	0.45/1.3	13.54	1.29	0.86	1.10	0.47	11.53
80	15.0	5.47	0.45/1.3	0.45/1.3	0.45/1.3	13.81	1.29	0.83	1.06	0.46	11.73

[1] Thermal conductivity of the HCB is conservatively assumed low due to drying during the early years in the repository (i.e., within ~30-years of heating in Figure 4) and high due to saturation at later heat peak (~700 years). Each HCB layer is 100-mm thick (Table 1).

[2] Initial Panel Thermal Load (i.e., localized heating between containers and rooms within a panel at the time of waste emplacement).

[3] Initial Gross Thermal Load (i.e., total heating over the entire area of the repository including the perimeter tunnels at the time of waste emplacement, assuming instantaneous loading).

No significant increase in uranium packing densities or decrease in repository volumes (i.e., costs) can be achieved when the second temperature peak controls the design. The effect of diminishing results is clearly illustrated in Figure 5. Maximizing the density of the containers (i.e., shown as uranium (U) density) reduces the area of the repository and its corresponding excavated volume while meeting the temperature design limit. The initial panel thermal load (IPTL) is maximized with 50-year-old used fuel.

The IPTL is defined as the localized heating rate at the time of container emplacement without the effect of the nonheating areas of the repository (i.e., the heat output of the container at the time of emplacement divided by both the container spacing and the room spacing, W/m^2). Not only does the heat output diminish with time, so does the emplacement area until the first temperature peak drops below that of the second peak (Figures 4 and 5). Beyond this point, the U density, the repository area and the repository volume do not significantly change.

III. IMPLICATIONS ON COSTS AND PROCESSES AT ELEVATED TEMPERATURE

Repository area, volume and, therefore, related excavation and sealing/backfilling costs can decrease if designers take advantage of the increasing age of used fuel prior to disposal as illustrated in the previous section. The practical time limit of increasing the age of used-fuel for this example of horizontal-borehole emplacement is about 50 years, beyond which no significant reduction in repository area, volume and direct cost can be achieved. Similar types of results have been produced for other waste emplacement configurations.[8] The cost-effective time limit for storing used CANDU® fuel, from the perspective of direct repository costs, appears to be in the range of 50 to 70 years depending on the specifics of the case. No corresponding used-fuel storage costs have been considered in these analyses.

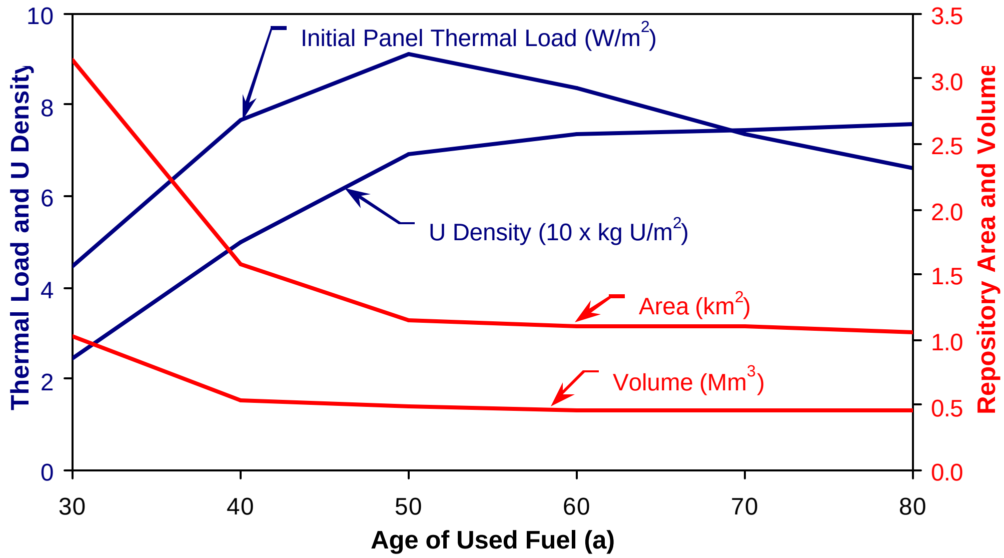

Figure 5: Effect of increasing the used-fuel age on repository thermal loading, fuel density, area and repository volume.

However, for a fixed quantity of used fuel, only the waste-emplacement portion of the repository (i.e., emplacement rooms and access tunnels) is cost sensitive to the age of the used fuel. All other DGR project costs including siting, licensing, surface facilities and infrastructure, containers and packaging, administration and management are relatively insensitive and fixed. Therefore, the expected savings in the direct repository cost due to aging the used fuel should be small in context to all the other DGR project costs listed above.

An important implication from designers increasing the uranium density is the increase in horizontal stresses in the granite due to thermal expansion. As the U density in the repository increases with the increasing age of the used fuel (Figure 5), the average rock temperature in the centre of the repository will also increase (e.g., dashed lines in Figure 4). Thermally induced horizontal stresses (σ_{HT}) will increase linearly with this temperature increase (ΔT) due to the lateral confinement provided by the surrounding rock by approximately:[9]

$$\sigma_{HT} = \frac{\alpha E \Delta T}{(1-\nu)} \qquad (1)$$

where a = coefficient of thermal expansion (strain/°C);
E = Young's modulus (GPa);
?T = temperature increase from ambient (°C).
ν = Poisson's ratio.

Since the overlying rock is less confined in terms of movement, the rock is somewhat free to displace upwards. Therefore, while increases in average rock temperatures result in greater vertical displacements, the thermally induced vertical stresses (σ_{VT}) are expected to be a fraction of the thermally induced horizontal stresses, by approximately:

$$\sigma_{VT} = \frac{\nu}{(1-\nu)} \sigma_{TH} \qquad (2)$$

The horizontal stresses (σ_H) in the Canadian Shield are generally greater than the vertical stress (σ_V) (i.e., $\sigma_H > \sigma_V$).[10] Waste emplacement rooms with circular cross-sections, such as the example horizontal-borehole emplacement method considered in this analysis, at a depth of 1000 m, may or may not be structurally stable for the prevailing stress conditions during excavation and are more likely to develop excavation damage zones or to fail with increasing thermally induced horizontal stresses. This can be wholly or partially remediated by use of elliptical or oval room geometries, which can be designed to be more effective than circular geometries in structurally resisting the increased thermally induced stresses.[11] Costs could increase since elliptical or oval geometries may be more difficult to excavate and the room volumes are likely to increase.

Another important implication from designers increasing the uranium density is the elevated long-term temperatures. Possible effects that should be considered include the following:

- chemical reactions;
- microbial activity; and
- cementation of swelling bentonite in the sealing materials.

The Arrhenius equation suggests that the higher the temperature, the faster a given chemical reaction will proceed. Also, the longer the duration of elevated temperature, the greater is the chance that reactions will occur as reactants and reaction products migrate within and through the DGR system. The chemical regime in the DGR should be re-evaluated in the context of the revised temperature regime if older used fuel is disposed at higher uranium densities.

Microbial-induced corrosion (MIC) of used-fuel containers would also need to be re-evaluated.[12] The solid lines in Figure 4 show that the early period of heating on the surface of the container is less rapid and less intense as the age of the used fuel increases. If peak temperatures occur after the sealing materials become water saturated, no subsequent drying of these materials is likely to take place. The evolution of the thermal and water-saturation regimes in the sealing materials adjacent to the container may affect both the early and the long-term microbial activity, thus the MIC, on the container surface.

Although the short-term effects are likely to be small for hot-water and vapour on the swelling capacity and the hydraulic conductivity of unsaturated bentonite at temperatures $<100°C$, the longer-term effects are not clear, particularly on saturated bentonite in a saline environment.[13,14] Cementation of bentonite clay particles by the dissolution and precipitation of silica is one observed mechanism of sealing-material alteration, which should be re-examined in the context of a much longer duration of elevated temperature.[15,16]

IV. CONCLUSION

The brief analysis for this example of horizontal-borehole emplacement shows that the repository volume and area can be significantly reduced (e.g., approximately by a factor of two) by increasing the age of used fuel from 30 to 50 years prior to disposal. This could allow a reduction in direct excavation and backfill material costs and may simplify locating a repository (e.g., to avoid fracture zones). Beyond a used-fuel age of about 50 to 70 years, depending on the specifics of the waste emplacement method, no further significant reductions in volume and costs can be realized. However, reducing the repository volume may have other negative implications that would need to be considered as part of a future design optimization process for a deep geologic repository, including feedback from performance and safety assessments.

ACKNOWLEDGEMENTS

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