Implications of Placing High Burnup Used Fuel in a Deep Geological Repository

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ABSTRACT

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Abstract

The Nuclear Waste Management Organization is examining the implications of high burnup fuel in the design of a deep geological repository.

In assessing any implications, this study was completed by assuming that the fuel to be stored is high burn-up fuel from an EPR advanced reactor with a mean burn-up of 50 MWd/kg U. Data available in the open literature from the Finnish Program were used and extrapolated to relevant Canadian geological conditions using gneiss rock for the EPR DGR design.

The EPR DGR design has the same layout as the CANDU repository with an identical number of placement tunnels. The storage capacity of the EPR DGR (21,075 EPR fuel assemblies) is based on the number of assemblies that would generate the same amount of electricity (about 4,930 TWh_e) as the 3.6 million CANDU fuel bundles to be stored in a reference CANDU repository. This requires that the number of used fuel containers for the CANDU DGR (10, 000) is nearly doubled those for the EPR DGR (5,270).

The footprint of the DGR is primarily dependent on the decay heat load from the fuel in the used fuel containers, the distance separating adjacent placement tunnels, and, the heat transfer properties of the engineered barriers and the rock. Based on a maximum used fuel container surface temperature of 81^{o}C, the minimum spacing of the EPR containers in a CANDU DGR is estimated at 8.0 m when the distance separating the placement tunnels is 40 m. This compares with a borehole spacing of 4.2 m for the reference CANDU fuel repository. The longer distance between boreholes for the EPR fuel is mainly due to the higher heat load of their used fuel container (1830 W) over the CANDU fuel container (1285 W). Even though the spacing between the boreholes is doubled for the EPR fuel, the layout area and the length of the tunnels for the EPR DGR are nearly identical to the reference CANDU DGR.

The main difference between the two DGRs is the greater number of used fuel containers, nearly doubled for the CANDU fuel. The smaller cross section of the EPR placement tunnels also reduces the excavation effort. Reducing the distance separating the placement tunnels, increased the excavation efforts for the EPR DGR.

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1. INTRODUCTION

Currently, fuel in pressurized water reactors (PWRs) reaches routinely high burnups of 30-50 MWd/kgU. New advanced Generation III (GEN III) reactors such as the Areva EPR and the Westinghouse AP-1000 are designed to achieve average burnups of 50-60 MWd/kgU. Both EPR and the AP-1000 reactors have been licensed in other nations and several are under construction. It is expected that these higher burnup reactors may be considered to replace the older aging fleet of reactors built in the 1960-70s and commonly known as Generation II (GEN II) reactors. The EPR and AP-1000 reactors offer increased safety features and larger generating capacities at a reduced cost.

The impact that the high burnup fuel from these new reactors might have on Adaptive Phased Management was first assessed by the NWMO in 2008 (Russell, 2008). This report adds to that assessment by detailing the implications of high burnup fuel in the design of a deep geological repository and specifically focuses on high burnup fuel with an average burnup of 50 MWd/kgU from Areva's EPR reactor.

In addition to Areva's EPR and Westinghouse's AP-1000 reactors, the enhanced AECL CANDU EC-6 reactor is of interest. This is a GEN III on-line fuelling heavy water PWR with safety and modularity features capable of delivering 740 MW power. The EC-6 is an evolutionary technology using natural uranium as fuel and based on the AECL CANDU 600 series built and operating in Argentina, Canada, China, Romania and South Korea. Construction experience has been good with deliveries meeting schedule and budget costs. In the case of China, their two units were completed ahead of schedule and under budget.

The higher fuel enrichment of the EPR and AP-1000 reactors leads to average burnups up to 60 MWd/kgU. The advanced reactors provide thermal efficiencies 10% higher than current reactors resulting in reduced fuel usage per TWh_e of electrical output. Details of the relative amounts of fuel being used can be found in the annual report on used fuel projections in Canada (Garamszeghy, 2012).

The uranium enrichment used by the EPR reactor is as high as 5% and the AP-1000 up to 4.5 %. Fuel for the CANDU EC-6 is natural uranium. The EPR fuel is expected to achieve on average 50 MWd/kgU which is about eight times the burnup of a GEN II CANDU reactor. The AP-1000 fuel burnups are comparable to the EPR fuel. The average EC-6 burn-up is about 7.5 MWd/kgU and is comparable to current CANDU GEN II reactors.

The higher burnups lead to higher heat of decays, the heat of decay being directly proportional to the burnup after a number of years in storage. On this basis, the EPR fuel will pose the greatest impact to a repository due to its higher thermal load. In this assessment, the EPR fuel will be used as a conservative boundary on how a DGR facility for CANDU fuel could be affected by a new nuclear build in Canada.

2. HIGH BURNUP FUEL CHARACTERISTICS

In this section, the focus of the discussion will be on those aspects of high burnup fuel, and, in particular EPR fuel, which are relevant to assessing its impact on the reference repository for the current fleet of CANDU nuclear stations being operated in Canada. Otherwise, comprehensive details of spent fuel characteristics for high burnup fuel can be found in a recent IAEA Series report (IAEA, 2011).

The design of the CANDU fuel bundle and EPR fuel are vastly different. One important parameter is the size and shape of the fuel assemblies which affects the size of the used fuel containers for placement in the DGR and the fuel handling operations at the Used Fuel Packaging Plant (UFPP). Figures 1 and 2 compare side by side the CANDU fuel bundle with the EPR fuel assembly.

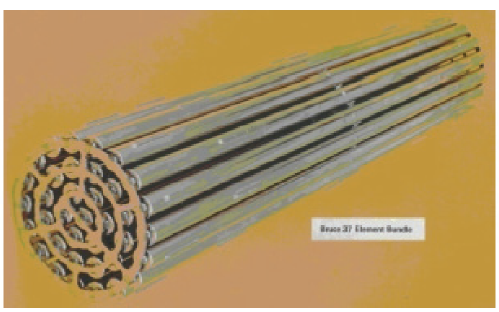

Figure 1: 37-Element CANDU fuel bundle (typical)

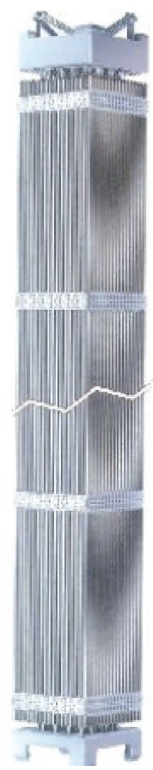

Figure 2: EPR fuel assembly

The CANDU EC-6 fuel bundle is identical to that shown in figure 1 having 37-elements or pins per bundle. This means that the reference CANDU DGR is equally well applicable to the storage of EC-6 fuel. The CANDU fuel bundle is a cylindrical array about 0.010 m in diameter with fuel pins 0.5 m long and weighs about 20 kg. The EPR fuel assembly is square prismatic in shape (17x17 pins in the lattice in a 0.214 m square array) and 4.8 m in length weighing about 180 kg. This difference in shape, size and payload has a marked impact in the design and operations of the repository.

Other differences include the amount of fissionable material, the average burnup of the fuel and the cladding material. The average EPR fuel burnup is about six times that of the CANDU fuel. These details are summarized in Table 1.

Table 1: Physical Characteristics of CANDU and EPR Fuel

Characteristics	CANDU Fuel (Bruce bundle)	EPR Fuel Assembly
Physical dimensions	102.5 mm OD x 495 mm OL	214 mm square x 4865 mm OL
Mass	19.2 kg U (21.7 kg as UO_2) 2.2 kg Zircaloy in cladding, spacers, etc 24.0 kg total bundle weight	527.5 kg U (598.0 kg as UO_2) ~182 kg other materials in cladding, spacers, etc 785 kg total assembly weight
Fissionable material	Sintered pellets of natural UO_2	Sintered pellets of UO_2 enriched up to 5% U-235
Average burnup	8.3 MWd/kgU (200 MWh/kg U)	50 MWd/kgU
Cladding material	Zircaloy-4	M5

An assessment of high burnup fuel characteristics and their implications to their management in a DGR has been reported by Xu et al, 2005. In their study, the implications of fuel with burnup higher than the current average burnup of 30 MWd/kgU realized in current reactors was assessed. This was done by incrementally increasing the fuel burnup to 150 MWd/kgU. The resulting higher radioactivity component and heat of decay of the higher burnup fuel was used to assess their impact on a DGR using as common basis the energy produced by the fuel in terms of TWh(e) per kg U. Their study found that there is a transition between 10-100 years post reactor life where the impacts of higher burnup are significant. This range coincides with the high heat of decay from the fission products, predominantly Sr-90 and Cs-137. However, outside and beyond this region, the higher burnups benefit the DGR design by reducing the surface area/capacity required to place the fuel for the same amount of electricity produced.

Repositories are particularly sensitive to the heat load placed on them by the stored fuel. The amount of energy in the form of heat generated by the fuel radioactive decay and the amount of fuel to be stored determines the maximum heat load of the container, and, hence its size. Then, the heat load of the container determines the spacing that must be maintained between containers to meet the repository design requirements such as allowable temperatures on the buffer barrier and the surface of the container.

Typical values for space requirements to store spent fuel from various reactors have been assessed since the 1980s. A summary of relevant results from those studies is summarised in Table 2 as presented by Allan and Dormuth (1999). The results are based on hard rock and directly relevant to the reference CANDU DGR which is assumed to be sited in gneiss rock.

Table 2: Typical DGR Layout Areas per TWh(e) (after Allan and Dormuth, 1999)

Country	Waste Form	Fuel Burnup (MWd/kgU)	Storage Period before DGR Placement (years)	Placement Method	Repository Placement Area (Approx.) (m^2/TWh)
Canada	Typical CANDU Fuel	7.9		Vertical boreholes in floor of room	400
Canada	Typical CANDU Fuel	8.3		In-room placement	660
Sweden	Used BWR Fuel Used PWR Fuel	35 39	≈ 40	Vertical boreholes in floor of room	500
Finland	Used BWR Fuel	35	20-40	Vertical borehole in floor of room	500-900

For the current assessment, the average burnup of the EPR fuel is set to 50 MWd/kgU while the CANDU fuel at 8 MWd/kg U. The dependence of heat of decay as a function of storage time for various fuel burnups is shown in figure 3. The data also shows the contribution to the heat of decay from the fission products which progressively decreases with time and at 200 years is rather negligible even for 100 MWd/kgU burnup fuel. Similar heats of decay were used in this assessment. In figure 4, the heat of decay for a “fictitious” but equivalent CANDU fuel bundle with the same burnup and decay heat characteristics of a 50 MWd/kgU EPR fuel is shown.

In the first 200 years of the post-reactor in service life, the heat of decay of the fuel is predominantly due to the decay of the fission products, in particular, Sr-90 and Cs-137. Thereafter, the heat of decay is mainly from the actinides, primarily americium and plutonium. Hence, the current international effort on the processing and transmutation of the minor actinides as a basis for significantly reducing the radioactive lifetime of the fuel from the order of a million years to about 400 years (see figure 5). Regardless, in adjusting the storage time of the fuel prior to placement, significant reduction on the requirements for heat dissipation of the repository can be achieved. To aid in the comparison with a CANDU based reference scenario as described in the NWMO report (SNC-Lavalin, 2011), the EPR fuel age will be set to 50 years old.

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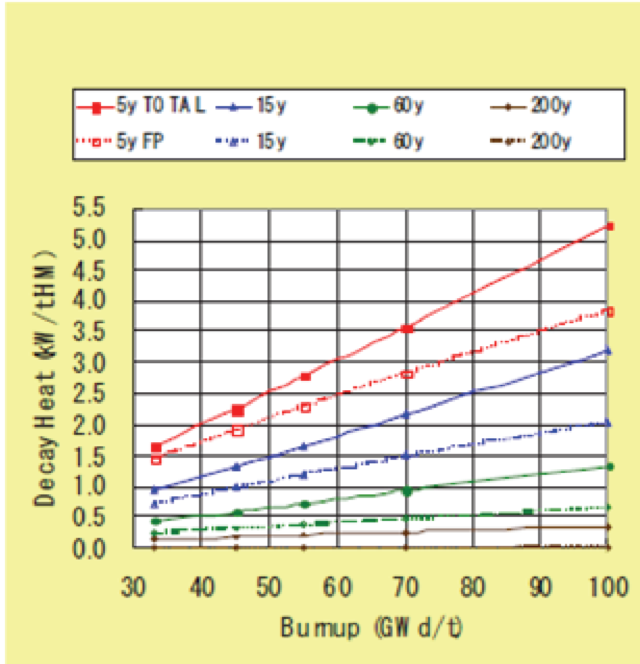

Figure 3: Heat of decay for UOx fuel in kW per metric ton of heavy metal as a function of burnup and cooling time (IAEA, 2010)

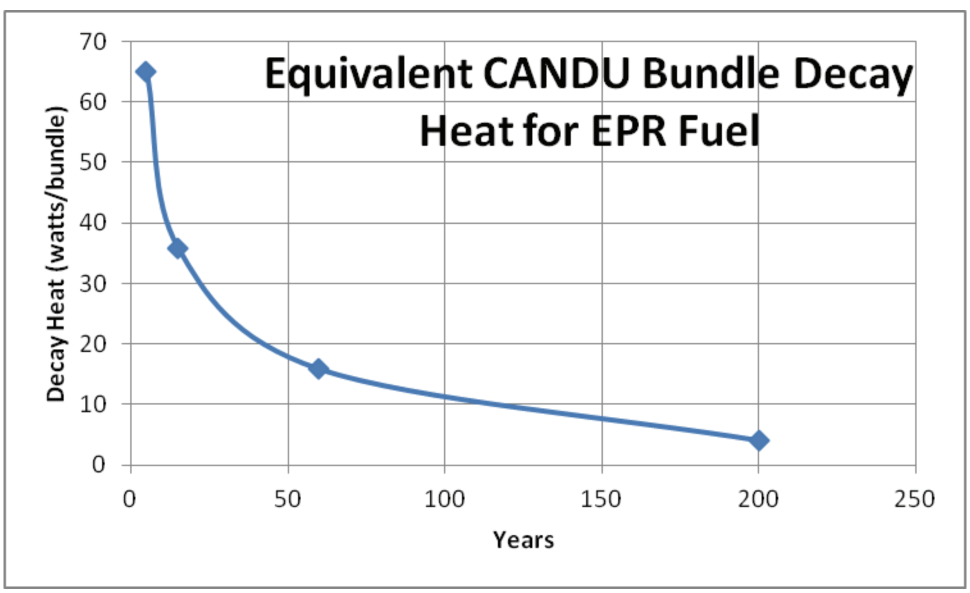

Figure 4: Heat of decay from an equivalent "fictitious" CANDU type fuel bundle if irradiated as EPR Fuel

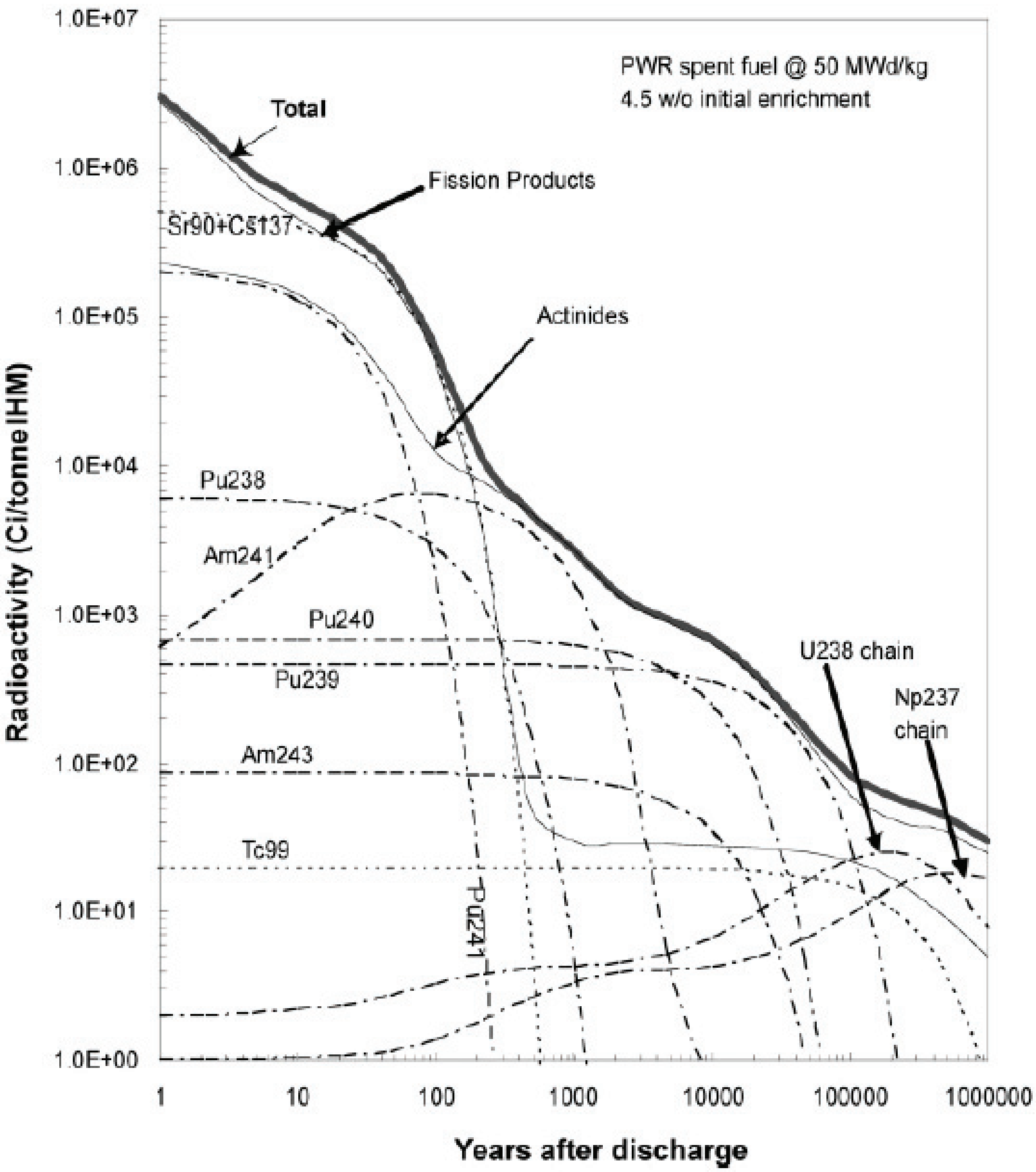

Figure 5: Radioactivity for 50 MWd/kgU burnup used fuel (After Xu, Kazimi and Driscoll (2005))

3. GENERAL IMPLICATIONS OF MANAGING HIGH BURNUP FUEL

Advanced fuels such as from EPR reactors place higher demands on the materials used to manufacture the assemblies. In particular, the fuel cladding as the first containment barrier to the release of radionuclides will have to meet higher requirements to ensure that the cladding remains intact during in-reactor life and through the post-reactor life management such as handling and transportation to a DGR. As a result, new materials and alloys such as M5 and ZIRLO are being used as cladding for high burnup fuel.

The new alloys offer significant higher resistance to hydrogen absorption and, consequently, greater resistance to Delayed Hydride Cracking (DHC). For instance, in dry storage, due to the much higher heat of decay, higher temperatures during storage will be expected. The higher temperatures will, for instance, increase the sensitivity of the fuel assembly to Delayed Hydride Cracking by the potential re-orientation of the hydride platelets from a circumferential to a radial orientation. This re-orientation of the platelets would be of critical importance to maintaining the mechanical integrity of the fuel during transportation. Hence, the need that the new cladding materials are less susceptible to DHC by reducing the hydrogen content in their matrix. Reorientation of the hydride platelets, however, is not expected for lower burnup fuels such as those for the CANDU EC-6 due to much lower temperatures during dry storage.

For EPR fuel, the cladding of the fuel rods is made of alloy M5. This is a zirconium 1% niobium alloy introduced in 1997 with superior properties during irradiation over standard zircaloys. The improved properties of M5 are achieved by total re-crystallization of the microstructure of beta-niobium second phase particles and by limiting the concentrations of iron, oxygen and sulphur. The absence of tin (less than 100 ppm) leads to lower corrosion rates and reduced hydrogen uptake. The oxidation corrosion films are thinner (40 μm) than in standard zircaloys. In particular, M5 shows irradiation growth and creep resistance to 80 GWd/Mg U burnup. Its in-reactor uptake of hydrogen remains below 100 ppm as a result of the low corrosion rates. Garner and Mardon, 2011, report that by mid-2010, 3.2 million fuel rods clad with the M5 alloy had been irradiated in PWRs to burnups of 80 MWd/kgU in 13 countries with acceptable performance.

The AP-1000 fuel cladding uses Zirlo™ alloy developed by Westinghouse. The Zirlo alloy is similar to zircaloy but with a lower concentration of tin, giving the alloy higher corrosion and creep resistance at higher fuel burnups. On a comparable basis to Zircaloy-4, Zirlo has a corrosion rate less than 0.6 times that of Zircaloy-4, its irradiation growth rate is 0.5 times and its creep rate 0.8 times. Uptake of hydrogen is comparable to Zircaloy- 4 (Sabol, 2010). Zirlo's resistance to creep and irradiation growth helps to maintain the diametral dimensions of the cladding during its in-reactor life. As in the case of M5, the low corrosion rates also ensure the oxide films will not become thick enough at the higher burnups to reach the second phase of Zircaloy oxidation where a much higher rate of oxidation occurs leading to run-away oxidation.

At a difference with lower burn-up fuel, higher burn-up has been observed to lead to higher crud deposits on the cladding. Regions of distinctive crud patterns (DCP) have been identified on the outward facing side of external rods in assemblies but not in the inner fuel elements. This crud appears thicker and denser than in more typical fuel. With thicknesses between 33 μm and greater than 100 μm on PWR fuel that compares to less than 25 μm for typical PWR fuel. The thicker crud might pose contamination challenges during handling in subsequent stages of the fuel management. Further, the crud acting as an insulation layer to the fuel rods may contribute to higher fuel temperatures during their storage. The end result is a higher centre line temperature of the fuel rods that could have some impact on other potential cladding degradation processes such as creep.

Along with higher crud deposits, longer in-reactor in-service times result in higher corrosion levels for the cladding - up to 100 μm for Zircaloy-4 in PWRs. The main result is a reduction in the thickness of the cladding as much as 10%. New materials such as Zirlo also experienced higher corrosion but generally their oxide thickness is less than that experienced by high burnup fuels using Zircaloy which develop thicker oxides.

Higher radiation fields are also a consequence of higher burnup. This will impact safety considerations but also the degradation of materials. At a difference with natural uranium CANDU fuel, the 5% enriched EPR fuel has a significant neutronic field (see Figure 6). This raises issues regarding the criticality of the fuel during its handling, storage, placement, as well as, post-placement.

The higher burnups relative to CANDU fuel leads to a higher content of radionuclides and to greater mechanical damage to the UO_2 pellets. In a DGR environment, this will have an impact on the safety analysis due to the larger source of radionuclides available for dispersion and the possibility that leaching of the fuel might also be enhanced.

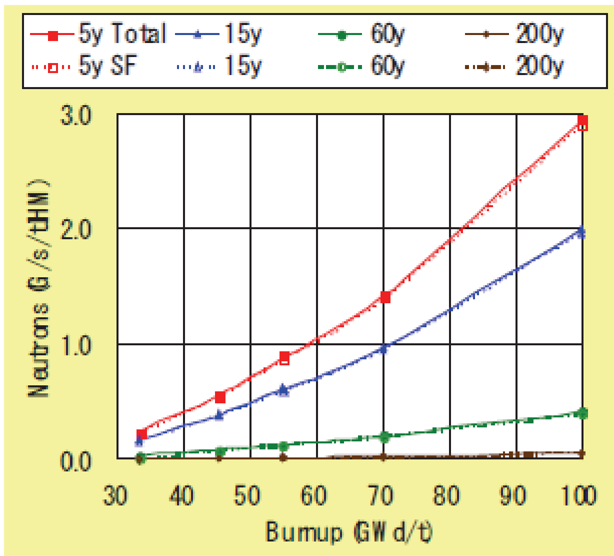

Figure 6: Neutronic Field for UOx fuel in (Giga neutrons per second) per tonne of Heavy Metal as a function of burnup and cooling time (IAEA, 2010). SF stands for spontaneous fission neutrons

4. CANDU USED FUEL DEEP GEOLOGICAL REPOSITORY

The reference CANDU repository for used fuel has specific requirements for managing the heat of decay generated by the fuel and its effect on both the radionuclide retention barriers and the rock mass. These requirements would apply as well to a repository storing EPR fuel.

The CANDU DGR is constructed at a depth of 500 m. An overall perspective of the DGR is shown in Figure 7. For the purpose of this assessment, the general layout of a DGR for EPR fuel will be similar to the layout for the reference CANDU DGR (see Figure 8). A panoramic view of the DGR surface facilities including the Shafts, the Used Fuel Packaging Plant (UFPP) and Auxiliary Facilities is shown in Figure 13.

Key requirements for the DGR are generally given in terms of the maximum temperatures that the bentonite buffer and the rock can be exposed to. They are effectively met by controlling the heat load per surface area of the repository, and achieved by specifying longer periods of cooling for the fuel post-reactor service, controlling the spacing of the used fuel containers and by the overall layout of the repository. Of particular importance, the temperatures in the repository should not lead to stresses in the rock that will compromise its structural stability and the buffer will not experience temperatures that will jeopardize its radionuclide retention properties.

The reference CANDU used fuel DGR has storage capacity for 3.6 million CANDU fuel bundles to be stored in 10,000 used fuel containers. The CANDU DGR layout is detailed in Figure 8 (SNC-Lavalin, 2011). The containers are placed in vertical boreholes excavated in the rock floor of the placement rooms.

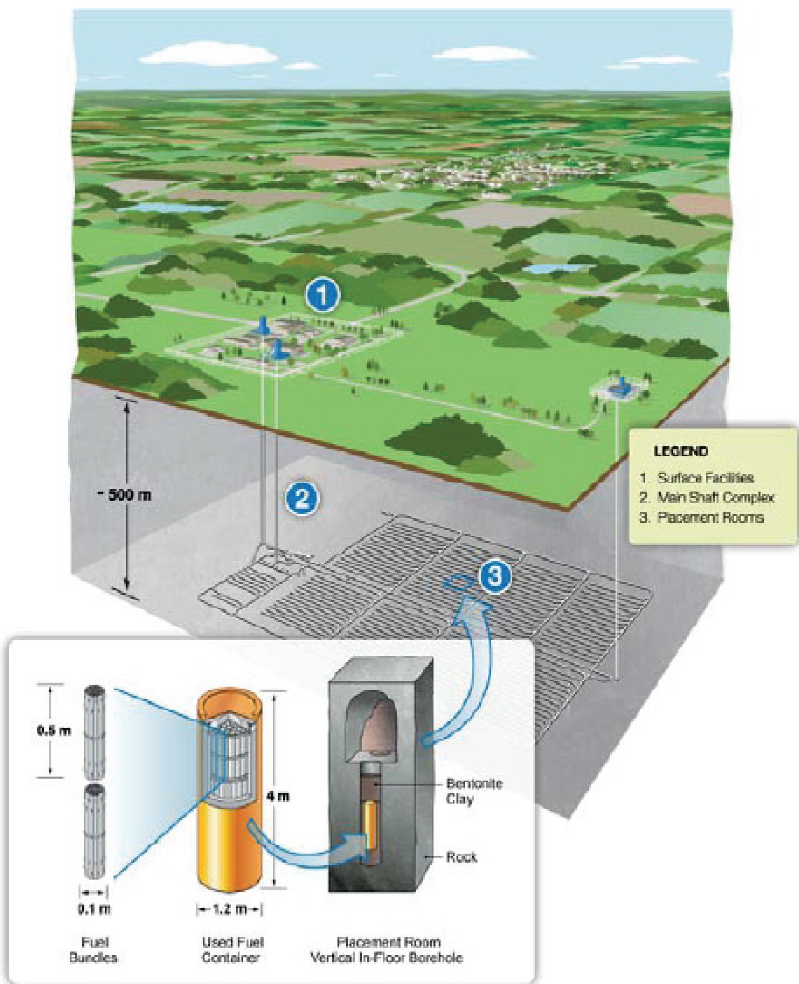

Figure 7: Overall view of the Reference CANDU DGR

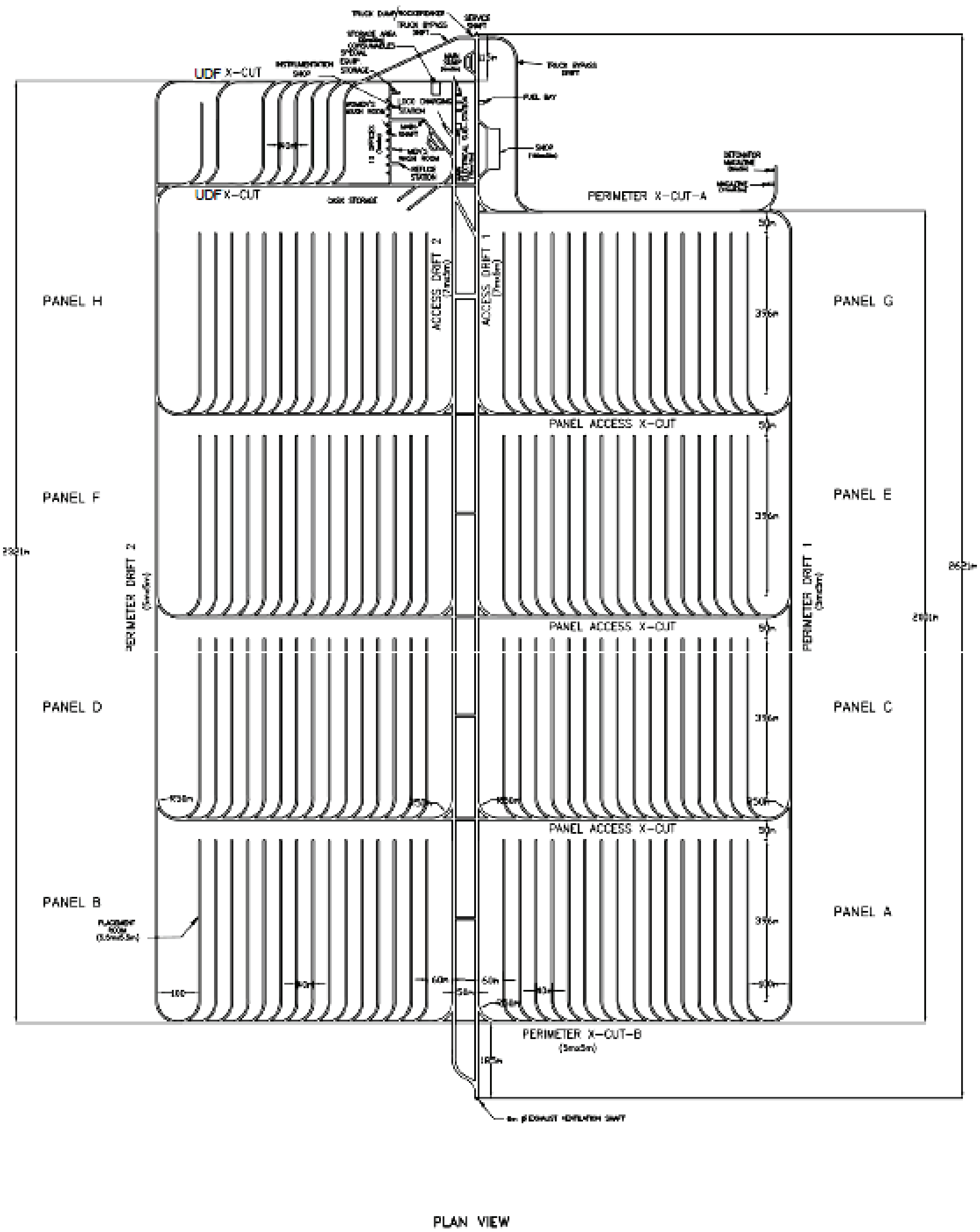

Figure 8: Plan view of the layout of the reference CANDU DGR for 3.6 million bundles

From the nuclear station sites, the fuel is transported to the Used Fuel Packaging Plant at the DGR site where it is transferred to the used fuel containers for placement in the repository. The containers are made of copper with a C-steel insert to provide structural stability to the outer copper shell. The storage capacity of a container is 360 bundles. The CANDU fuel loaded into the containers to be emplaced in the DGR would have cooled for at least 30 years prior to their placement in the DGR. For a typical 30 year old CANDU fuel, using as a reference a 37-element Bruce bundle, the heat of decay is about 3.6 W/bundle. As a result, the used fuel container gives off 1300 W heat when first placed in the DGR.

The geology of the repository is hard rock gneiss with a thermal conductivity of 3.0 W/m K. The surface ambient temperature is 5 ^{o}C and the geothermal gradient in the rock is 0.012 ^{o}C/ m. Hence, the ambient rock temperature at the DGR level is 11 ^{o}C. By comparison, the Finnish repository assumes a depth of 400 m with a rock temperature of 10.5 ^{o}C.

The temperature that the bentonite buffer can be exposed to without its radionuclide retention capacity affected is 100 ^{o}C. For CANDU fuel 30 years old, the appropriate centre-to-centre distance between the boreholes has been estimated at 4.2 m when the placement tunnels are located 40 m apart. For this spacing, the maximum surface temperature of the used fuel container is 81 ^{o}C after 16.5 years following container placement. The maximum temperature of the rock at the floor level of the placement corridor and in between the emplaced containers is expected to rise to about 55 ^{o}C at 60 years after placement and marginally higher than 55 ^{o}C shortly after 1000 years. Thereafter, the temperature decreases steadily. In assessing the placement of EPR fuel, the container surface temperature was specified to match the CANDU used fuel container surface temperature of 81 ^{o}C. The centre-to-centre distance for the boreholes was then estimated based on this temperature.

In the placement corridors, there are 89 boreholes per corridor with one container per borehole (see fig. 9). The boreholes diameter is about 1.97 m and the container outer diameter is 1.25 m. This leaves an annular space of about 0.35 m thick between the container and the rock. It is filled with three rings of bentonite. The middle ring about 0.250 m thick is made of compacted bentonite with a thermal conductivity of 1.0 W/m K. The inner and outer rings provide the transition between the container and the compacted bentonite and the compacted bentonite and the rock, respectively. Both are made of bentonite pellets. Their thicknesses are about 0.050 m with a thermal conductivity of 0.40 W/m K. The thermal properties of the bentonite barrier and the rock relevant to this study are summarized in Table 3.

Table 3: Thermal Properties of the Bentonite and Gneiss Rock

Material	Thermal Conductivity (W/m K)	Specific Heat (J/kg K)
Highly Compacted Bentonite	1.0	1280
Bentonite Pellets Gap Fill	0.4	870
Gneiss Rock	3.0	845

Based on the storage capacity of the repository, 10,000 containers will be placed. However, the capacity of the DGR layout has a contingency for an additional 10% of the required boreholes. This provides spare capacity in the event of finding unfavorable rock and/or hydrogeologic conditions and boring boreholes that fail to meet quality specifications.

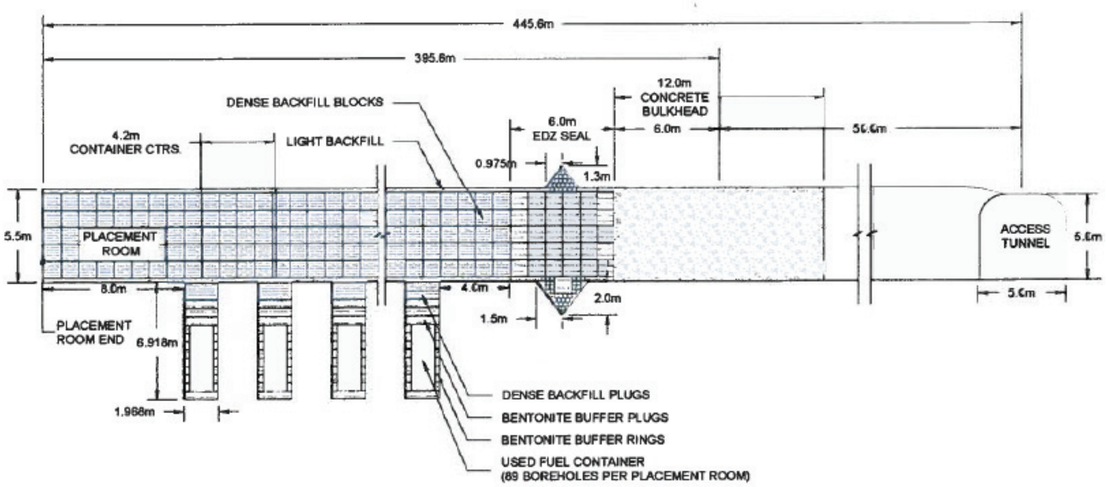

Figure 9: Longitudinal cross section of a typical placement tunnel in the CANDU DGR (SNC-Lavalin, 2011)

The basic layout for the placement tunnels of the repository is rectangular in shape and enclosed by the perimeter drifts (Figure 8). Based on a tunnel spacing of 40 m and borehole spacing of 4.2 m, its overall size is estimated at 1564 m by 2001 m. In addition to the placement tunnels, there is an adjacent area by the entrance to the repository as determined by the location of the main shaft dedicated to be a demonstration/test facility. On Figure 8, it is located contiguous to panel H and at the base of the main shaft and service shaft. The facility has a number of corridors separated 40 m apart which are of smaller size than the placement tunnels. These will be excavated 10 years ahead of the main panels and will be used to conduct rock characterization tests and tests with containers to confirm the design parameters for the repository.

The tunnels for the placement of the containers are distributed into eight panels numbered A-H. The panels are bounded by the perimeter drift. Within the perimeter drift, the panels are grouped into two groups of four panels each and separated from each other by the two parallel access drift corridors that run lengthwise along the main centre axis of the layout. These are used for the movement of trucks excavating new corridors and the vehicles used for the placement of the containers, both operations being done concurrently but in different areas of the facility. Both access drifts end at the main exhaust ventilation shaft situated at the opposite end to the entrance to the DGR by the main shaft and service shafts. The main and service shafts are used for the delivery of equipment and the used fuel containers from the surface.

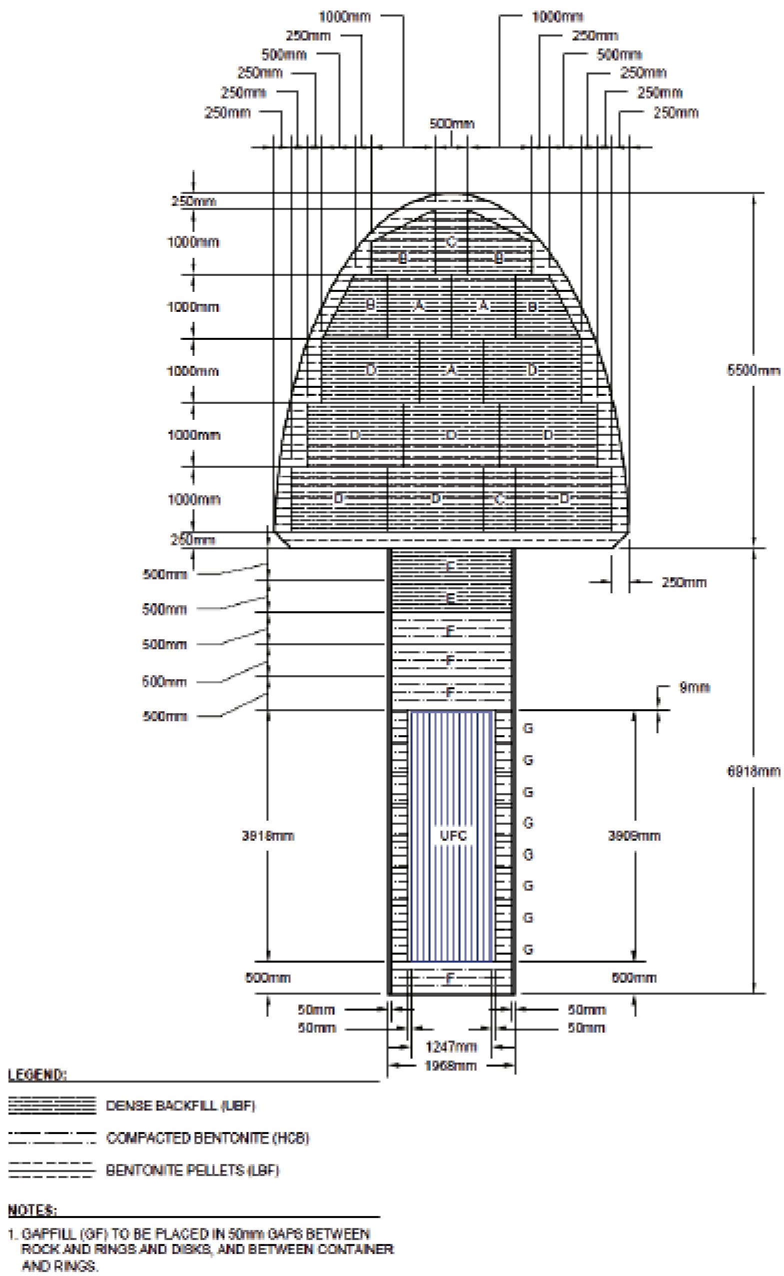

Figure 10: Cross section of the Placement Tunnel with the silhouette of a 1.8 m diameter and 6.9 m deep borehole (Carvalho and Steed, 2012). HCB is highly compacted bentonite; GF is the gap backfill made of bentonite pellets; DBF is the dense backfill and LBF is light backfill

Once the used fuel container is seal-welded in the Used Fuel Packaging Plant located at the surface, it is transferred to the DGR for placement in a borehole. The boreholes occupy the centre-line of the floor of the placement tunnels (Panels A to H in Figure 8). A longitudinal cross section of a sealed placement tunnel with details of the sealing arrangements is shown in Figure 9. The view covers the entrance portion of the tunnel and it illustrates what a tunnel looks like after the placement of the containers is completed and the tunnel is sealed by backfill and a concrete bulkhead.

Figure 10 shows the cross section of the placement tunnel with a borehole after backfilling both the borehole and the tunnel. The cross section is elliptical in shape with a height of 5.5 m from the floor of the tunnel and a width at the floor of 5.5 m. The borehole centered at the mid-point from the tunnel walls is 6.92 m deep with a diameter of 1.97 m.

To estimate appropriate ages of the fuel that could be placed in the repository to meet the required temperature specifications, the containers were modelled as a finite line heat source. This allowed for an analytical solution which compares favorably with a numerical approach using finite elements. Based on this solution, an estimate for the required spacing of the fuel containers storing EPR fuel is found. Chan (1980) found that a line heat source solution is simple and known to give temperatures for the rock that are nearly identical to those obtained from a finite line heat source. However, the finite line heat source would be closer to modelling the used fuel containers.

5. USED FUEL CONTAINER

The used fuel container (UFC) assumed for the Reference Base Case Scenario for CANDU fuel is a double wall container with an inner shell of C-steel and an outer shell of copper. The copper shell gives the container its corrosion protection which is estimated to last one million years. The C-steel shell provides the container with mechanical and structural stability. Similar containers for other high burnup fuel such as EPR and AP-1000 fuel have been proposed. Figure 11 illustrates the reference CANDU used fuel container and Figure12 shows a container for high burn-up EPR as proposed in the Finnish Nuclear Waste Program (Raiko, 2005). The Container for EPR fuel holds four fuel assemblies in the C-steel insert/shell. The cross section of the container is also shown at the top of the container illustrated in Figure 12. The container for AP-1000 fuel will be similar to the one shown for EPR fuel with capacity for four assemblies.

The current disposal container for CANDU fuel is based on NWMO container development work. The container can hold up to 360 CANDU fuel bundles in three steel baskets with two layers of fuel bundles per basket. The wall thicknesses of the copper and C-steel vessels are 0.025 m and 0.1025 m, respectively. The overall dimensions are 3.842 m height and 1.247 m in diameter. The container weighs 26.7 Mg when loaded with the CANDU fuel. The payload of the 360 used fuel bundles stored in the container being 8.64 Mg. A summary of the used fuel containers characteristics is given in Table 4.

Due to criticality considerations, the array provided by the C-steel insert maintains the fuel assemblies configuration during disposal to ensure non-criticality. The overall dimensions of this container are dictated by the number and size of the fuel assemblies. As a result, the container height is 5.25 m long and 1.05 m in diameter. The overall payload with the fuel assemblies loaded is 29.1 Mg. Table 4 summarizes the physical dimensions for both the CANDU and EPR used fuel containers.

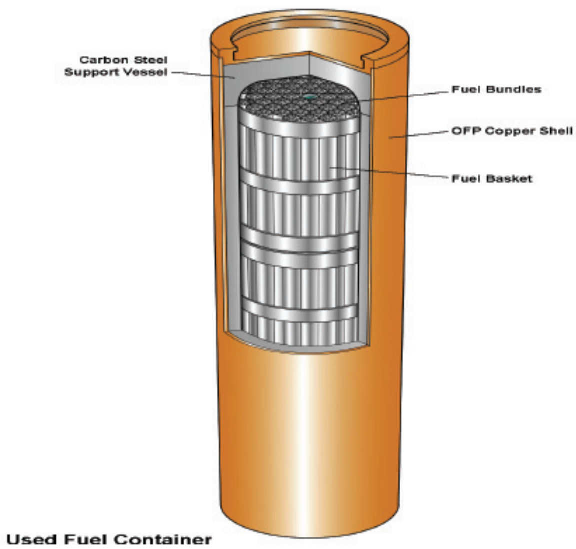

Figure 11: The CANDU reference Copper Used Fuel Container showing the fuel baskets for CANDU fuel bundles

Figure 12: Similar Copper Used Fuel Container for High Burnup EPR fuel showing the container cross section after Raiko, 2005

Table 4: Used Fuel Container Characteristics for CANDU and EPR Fuel

	Used Fuel Containers	
	CANDU	**EPR**
Number of Assemblies	360	4
Assemblies Total Weight (Mg)	8.64	3.14
Container Weight (Empty) (Mg)	17.06	26.0
Outside Diameter (m)	1.247	1.050
Height (m) *	3.842	5.25
Height (m) **	-	5.20

* As given by Raiko (2003) for the size of the EPR containers
** As given by Ikonen (2009) and used for the data in this study

6. USED CANDU FUEL PACKAGING PLANT (UFPP)

The interface of the DGR with the off-site used fuel transportation system takes place at the Used Fuel Packaging Plant (UFPP). The UFPP is located at the centre of the DGR site next to DGR Main Shaft as shown in Figure 13. In this facility, transportation casks containing used fuel from the various nuclear stations sites are received and unloaded. The fuel is then processed and transferred to used fuel containers.

The reference UFPP is a three storey reinforced concrete structure divided into two levels designated the transfer level and the operational level. A longitudinal cross–section of the UFPP showing both levels is given in Figure 14. The layouts for both the transfer and operational levels are shown in Figures 15 and 16, respectively. In particular, the facility is provided with two processing lines.

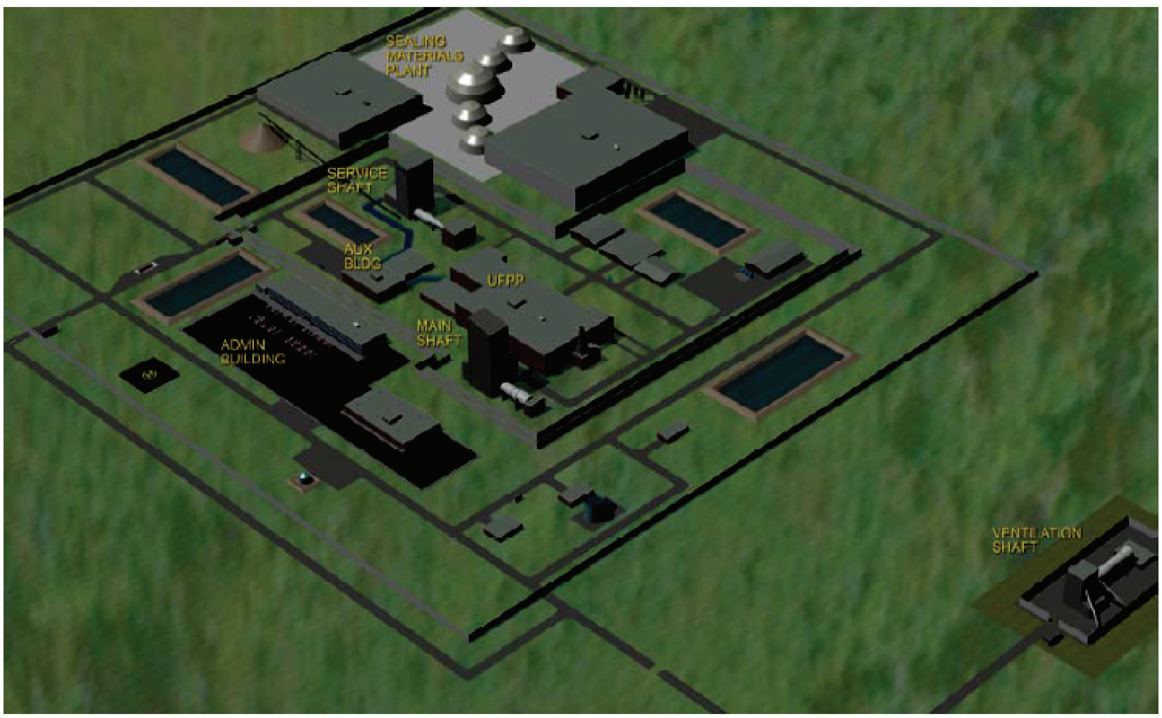

Figure 13: 3-D View of the DGR Surface Facilities, including the UFPP just north of the Main Shaft

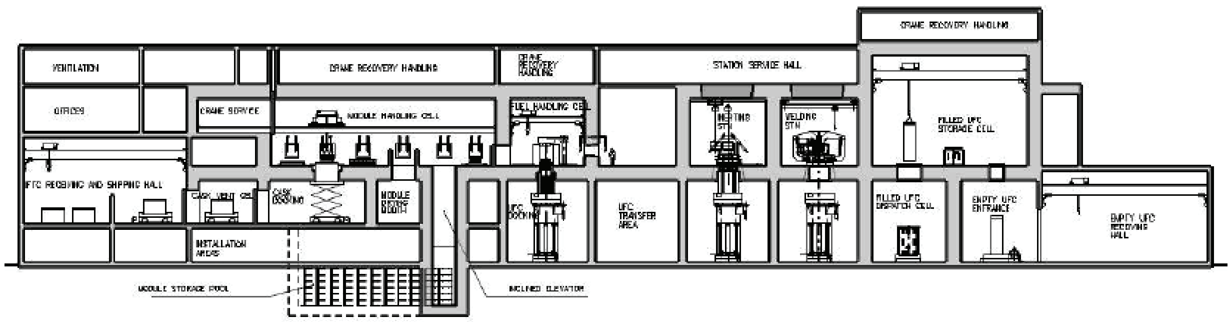

Figure 14: Longitudinal cross section of the UFFP showing the Transfer level (basement) and the Operational level above the Transfer level

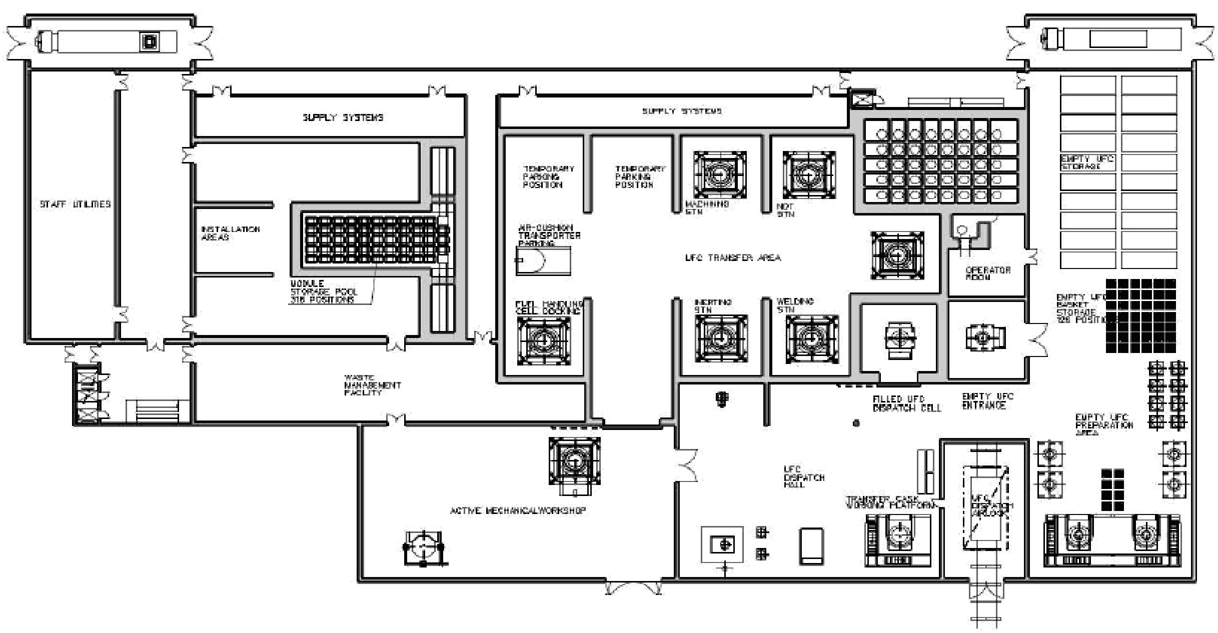

Figure 15: Plan view of the UFPP - Transfer level

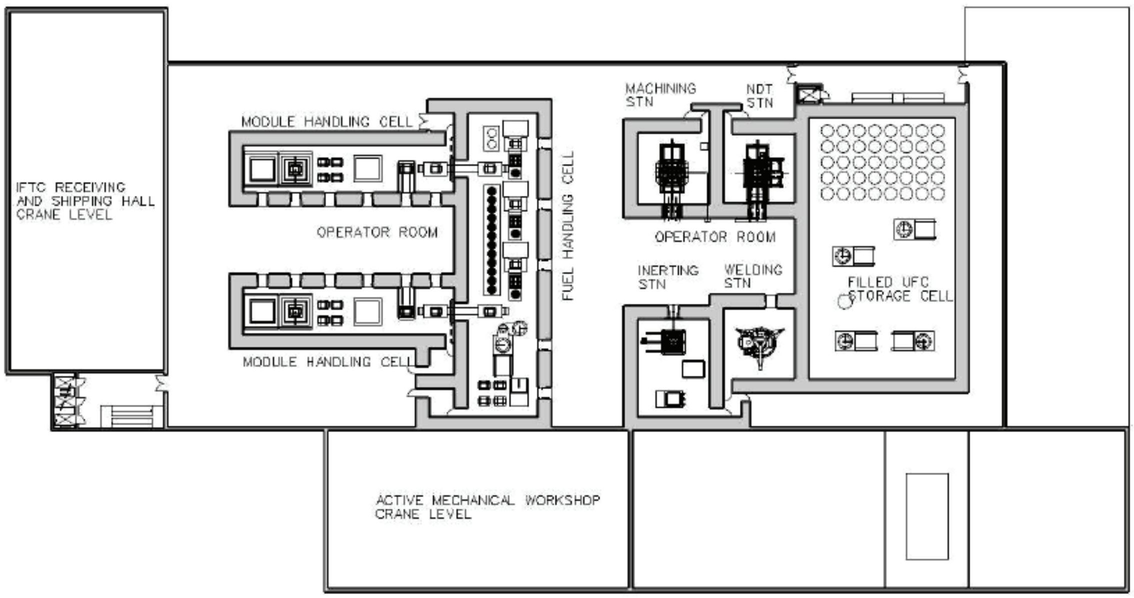

Figure 16: Plan View of the UFPP - Operational Level

In addition to receiving off-site transportation casks with the used fuel, the facility is also provided with bays for receiving empty used fuel containers, a storage pool for used fuel, facilities for unloading fuel from the transportation casks, and then loading it into the used fuel containers, seal welding, inspection, and, transfer of the used fuel containers to the repository. The facility has provisions for decontamination of transportation casks and for retrieval of used fuel from containers that have been found to be defective prior to placement. Most of the operations will be done remotely and shielding is provided for the purpose. The direction of air flow for the HVAC systems is from uncontaminated to contaminated areas and HEPA filters are installed to meet environmental regulations.

CANDU fuel is received at the UFPP in their storage baskets known as modules. The fuel is unloaded in their modules from the transportation casks inside the facility and into a Module Handling Cell (MHC) (Figures 14 and 16). Two parallel but independent MHCs are provided to receive the modules. The two MHCs connect with the Fuel Handling Cell (FHC). Depending on the availability of fuel handling capacity at the FHC, the modules are directed to the FHC or to a storage pool located in the Transfer Level of the UFPP, and, just underneath the floor of the Module Handling Cell (Figure 15). For CANDU fuel, the fuel bundles have to be transferred from the storage modules to the used fuel container baskets prior to encapsulation in the used fuel containers (UFCs). This is done in the Fuel Handling Cell (Figure16). This facility is provided with fuel handling equipment that remotely and automatically transfer the fuel from the modules to the UFC storage baskets.

Used fuel containers loaded with the fuel are seal welded, filled with an inert helium atmosphere and decontaminated. Container welds are machined, inspected and tested non-destructively in the Used Fuel Container Transfer Area (Figure15). Following the tests, released containers are transported directly to the repository or stored in the Filled UFC Storage Area for transport to the repository at a later time. Handling of the filled UFCs is done in an upright position within the UFPP in specially dedicated air cushioned shielded casks. Ready-to-dispatch UFCs are loaded into transfer casks at the UFC disptach hall at the end of the facility for delivery to the repository.

6.1 Implications of EPR Fuel to the CANDU UFPP

From the point of view of this assessment, the main focus will be in areas where the use of EPR fuel assemblies may affect the design and the provisions of the UFPP design for current commercial CANDU fuel. For instance, in the transfer and handling areas, the size of the EPR fuel assembly will have an impact on operations and processing equipment. Given the much larger payload and size, the use of a dedicated hot-cell for handling these fuel assemblies will be required, above all, to deal with the potential of damaged fuel following a handling or transportation accident.

Headroom will also be affected, and, it is expected to require design changes in the height of the ceiling of the processing rooms. A consideration as to whether the heights of the UFPP ceilings should be increased to accommodate assemblies such as those from AP-1000 reactors at this early stage of the UFPP design may be suggested for assessment. This up-front provision might reduce costs at a later stage in the program if new build of AP-1000 fuel type reactors is implemented.

Another area that will be affected by EPR or AP-1000 fuel is the decontamination facility. Its design will likely have to include provisions for dealing with potentially defective and damaged EPR type fuel. In this regard, the EPR assemblies have an almost order of magnitude increase in the amount of radionuclides, volatiles and gases over commercial CANDU. This will require design upgrades, for instance, in the HEPA filters for the facility ventilation system. Of particular consideration, is the observation that high burnup fuel experience thicker crud deposits than lower burnup fuel such as CANDU. The concern stems from the observation that pressurised water reactor high burnup assemblies show Distinctive Crud Patterns (DCP). This thicker crud deposit on the outer side of the cladding of the fuel elements, increases the risk of detachment of crud particulate during the handling of the EPR fuel assemblies in the UFPP, and, provisions will have to be made for this eventuality.

At a difference with CANDU fuel, the EPR fuel is not shipped to the UFPP in storage modules but simply as individual fuel assemblies. As a consequence, the fuel handling cell can be simplified since the fuel is not transferred from storage modules to storage baskets prior to encapsulation in the UFC but simply transferred to the UFC. However, given the length of 4.87 m of the EPR fuel asemblies, higher head space will need to be provided for the handling of the EPR fuel.

Individual fuel assemblies and fuel elements will most likely need to be handled individually. Given the size and radionuclide content of EPR fuel assemblies, this should be considered to be a “must” provision.

Similarly, the shielding requirements for the EPR fuel are more demanding due to the higher radiation fields, and, in particularly, the neutronic fields. In this respect, the EPR assemblies will add another provision to the UFPP not currently required for natural CANDU fuel having to do with criticality considerations for the assemblies. Special dedicated storage areas for both fuel and containers with adequate provisions to maintain the fuel in a non-critical configuration will have to be provided to reduce the neutronic fields and control the fuel reactivity or its criticality.

Designing the UFPP for the more stringent requirements of the EPR fuel assemblies would take care of the CANDU fuel. It is possible that co-location of processing lines for both types of fuel making use of common equipment where possible might be a way to add flexibility to the UFPP by having it capable of accomodating future changes in the reactor fuel such as from GEN III+ reactors.

7. IMPACT OF EPR FUEL ON THE REFERENCE DGR FOR CANDU FUEL

To compare the implications that EPR fuel has on the reference layout for a CANDU fuel repository, the repository layout for the high burnup EPR fuel was made in shape identical to the layout of the repository for CANDU fuel as illustrated in Figure 8. The only variation is that resulting from the length of the placement tunnels where the boreholes for the used fuel containers are excavated. The cross section of the tunnels for the EPR fuel follows the Finnish/Posiva design but it is quite similar to the reference CANDU repository.

The capacity of the repository for the EPR fuel is determined from the number of assemblies of EPR fuel with average burnup of 50 MWd/kgU required to produce the same amount of electricity in TWh_e as the 3.6 million CANDU fuel bundles stored in the reference repository for CANDU fuel.The estimate considers the efficiencies in the production of electricity by the GEN III+ EPR and the CANDU reactors, respectively.

The generation of electricity is usually quantified in terms of TWh(e)/kgU and is directly dependent on the fuel burnup. The higher the burnup, the more electricity is produced per kgU. As a result, also, higher burnup leads to a smaller amount of kgU that has to be placed in a repository. Consequently, a reduced number of assemblies has to be taken care of for the same amount of electricity produced, thus, giving an advantage to high burnup fuel in terms of reducing the number of boreholes required to place the fuel per kgU.

However, the high burnup fuel also leads to higher heat of decays that affect the design of the DGR components including the storage capacity of the used fuel containers. One key design parameter is the distance of separation between the boreholes in which the UFCs are placed. This separation distance between the boreholes depends in a complex way on the heat output per container, the separation between the placement tunnels, the design of the engineered barriers and the material properties of both the rock mass and the engineered barriers. As well, the allowable stresses, both mechanical and thermal, for the DGR system components, the excavated tunnels and boreholes and the rock mass may have an impact on the estimated distance separating the boreholes. This distance is calculated by a thermal analysis of the DGR design. For this assessment, based on a maximum allowable temperature of 81^{o}C for the used fuel container surface, the mechanical and thermal stresses in the DGR meet the criteria for safety (SNC-Lavalin, 2011).

7.1 Used Fuel Container Peak Surface Temperature

In order to estimate the peak surface temperature of the containers for EPR fuel placed in a repository, it is best to estimate used fuel container surface temperature in the repository as a function of the containers separation along their placement locations in the tunnels. For their derivation, the data provided on EPR fuel by Ikonen (2009) in his analysis for the thermal dimensioning of a proposed Finnish repository was used and adapted to the CANDU DGR. A comparison of the main characteristics between a used fuel container storing EPR fuel and CANDU fuel is shown in Table 5. Further details as to how the estimate of the separation distance between boreholes was calculated are given in the Appendix.

EPR fuel to be stored in the UFC would have been in storage for about 50 years prior to its placement in the DGR while the CANDU fuel would have been 30 years. For these storage times, the EPR container will have at the time of placement a nominal power of 1830 W and the CANDU container about 1300W. Even, at the longer period of storage of 50 years, the heat source from the EPR fuel is considerably stronger than the CANDU fuel thus requiring a significant larger distance of separation between boreholes than the CANDU containers.

Table 5: Used Fuel Container Initial Power and Fuel Characteristics

Fuel Type	EPR	CANDU
Initial Container Power (Watts)	1830	1296
Fuel Burnup (MWd/kgU)	50	9.2
Weight of Uranium per Fuel Assembly (kgU)	527.5	19.5
Fuel Heat of Decay (Watts/assembly)	458	3.6
Fuel Age (Years)	49.7	30
Container Initial Linear Heat Source Strength (W/m)	319	284

As indicated in the previous section, the data from Ikonen (2008) on the peak temperature for EPR fuel in a Finnish based repository was adapted to the CANDU DGR. This was done by re-calculating the data to take into account the different enginneered barrier system used in the reference CANDU DGR and, also, by making use of the previous finding that the temperature increase in the rock is inversely proportional to the thermal conductivity (see the Appendix). This allows correcting the data for the different rock matrix used in the CANDU DGR (gneiss rather than granite). The methodology used first estimates the temperature drop for the Finnish engineered barriers from the data supplied by Ikonen by taking into consideration that the maximum peak temperature occurs at about 20 years. Once the temperature of the rock for the Finnish repository is obtained, the rock temperature for the CANDU DGR repository is easily calculated by the inverse proportionality to their respective rock thermal conductivities. This temperature along with an estimate of temperature drop accross the CANDU DGR engineered barrier, allows for the calculation of the surface temperature of the container for EPR fuel in the CANDU based DGR.

The results of these calculations are summarized in table 6 for three centre-to-centre distances of 25 m, 30 m and 40 m between the tunnels, and, presented in graphical form in Figure 17. The data shows the peak temperature on the surface of the used fuel container exponentially decaying to an asymptotic value of about 70 ^{o}C corresponding to the case of a single container.

Table 6: Container Surface Peak Temperature in a CANDU DGR

Container Surface Peak Temperature For EPR /1830 W Container (°C)			
Distance Between Containers/Boreholes (m)	**Placement Tunnels Separation Distance = 25 m**	**Placement Tunnels Separation Distance = 30 m**	**Placement Tunnels Separation Distance = 40 m**
5			98.8
6		98.0	90.6
7	97.0	90.8	84.9
8	90.8	85.5	81.0
9	86.0	81.8	78.3
10	82.5	79.1	76.4
11	79.9	77.0	75.0
12	77.9	75.5	73.7
13	76.3	74.3	73.0
15	74.0	72.6	71.9
17	72.6	71.6	71.1
20	71.3	70.9	70.5

For the purpose of designing the layout of a repository for EPR fuel based on the reference CANDU criteria that the surface of the container should not exceed 81 C, the data indicates that for the tunnel separation of 40 m as used in the reference CANDU repository, the boreholes would have to be excavated 8.0 m apart. This compares with a value of about 14 m for the Finnish DGR, highlighting the CANDU DGR design as more effective in removing the heat from the fuel. This effectiveness is due to the higher conductivity of the gneiss rock considered for the CANDU DGR over the granite rock of the Finnish DGR and the higher heat transfer of the CANDU DGR engineered barriers highlighting the importance of the engineered barrier to heat dissipation. By reducing the distance between the placement tunnels, the data shows increasing distances of separation between the boreholes are required being 10.6 m at a distance of 25 m. This is about 30% greater distance than for the 40 m tunnel separation.

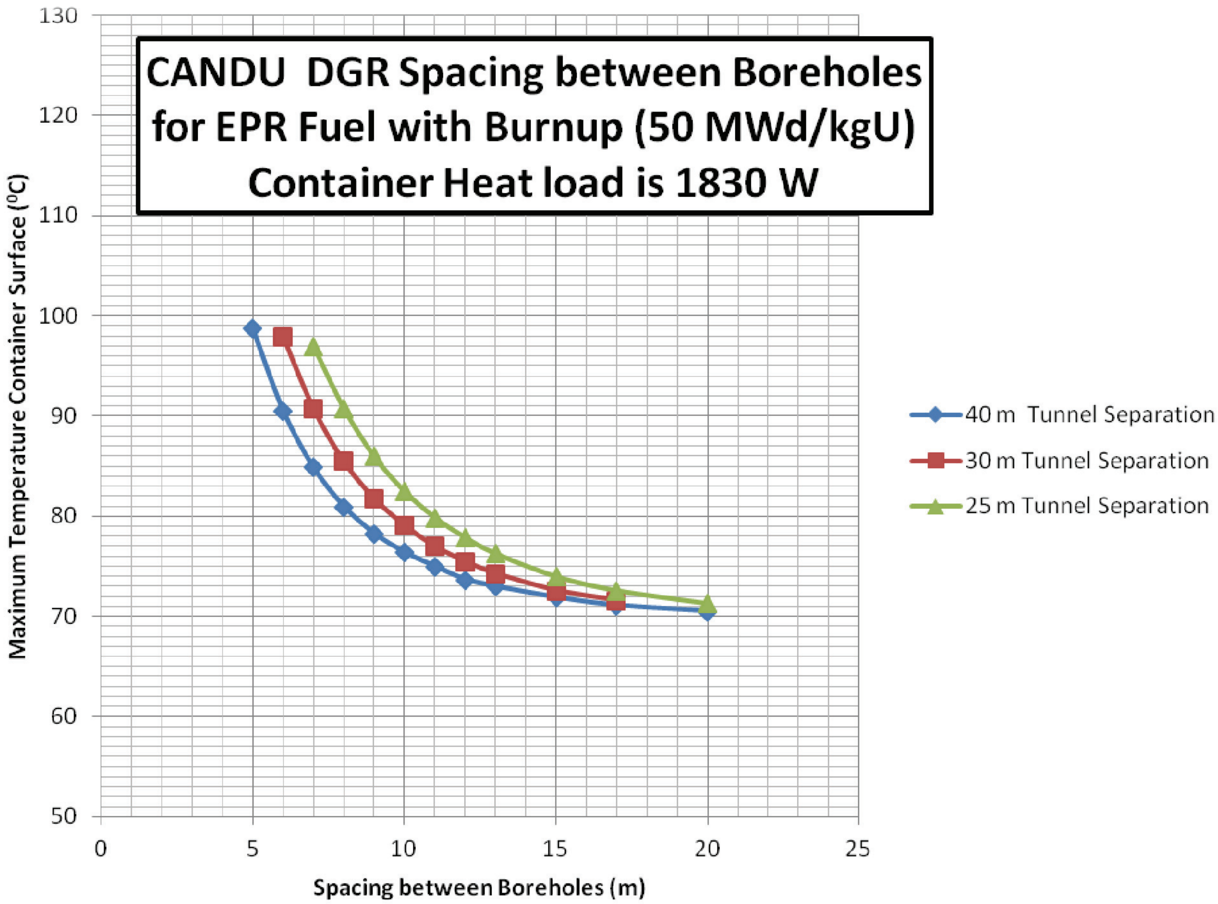

Figure 17: CANDU DGR spacing between boreholes when storing EPR fuel containers with a heat load of 1830 W

7.2 Impact of the EPR Fuel on the CANDU DGR Layout

The layout for the EPR DGR follows a similar pattern as the reference CANDU DGR with an identical number of tunnels as the CANDU DGR but of different length. In order to aid in assessing the implications of the EPR fuel to the reference CANDU DGR, the storage capacity of the EPR DGR is based on storing an amount of EPR fuel that would produce the same amount of electricity as the 3,600,000 bundles stored in the reference CANDU DGR.

The Reference CANDU DGR will store 10,000 used fuel containers with a storage capacity of 360 fuel bundles per container. This would translate to a DGR with 10,000 boreholes, however, the design includes a contingency of 10% in the number of boreholes that will need to be excavated to allow for boreholes that will fail to meet the design specifications for various reasons such as unforeseen poor rock conditions and hydraulic conductive zones. As a result, it is estimated that the DGR is excavated with 11,000 boreholes.

For the EPR fuel, one 50 MWd/kgU EPR assembly has been estimated to produce 0.234 TWh_e based on an electrical efficiency of 37% (Areva, 2005). The reference CANDU bundle is estimated to produce 0.00137 TWh_e assuming a typical 31% efficiency for the CANDU reactor. Since 3,600,000 bundles are to be stored at the CANDU DGR equivalent to 4,930 TWh_e, the number of EPR assemblies producing the same electrical power are estimated at about 21,075. Since four assemblies are stored per EPR container, the number of EPR containers to be stored in the DGR is 5,270 containers. Allowing for the 10% contingency in the number of boreholes, the EPR DGR is assumed to be built with 5,797 boreholes.

The tunnels in the layout of the DGR can be divided into the following main groups:

1. Placement Tunnels
2. Perimeter tunnels
3. Central Access drifts and corridors in-between the drifts
4. Panel Access X-Cut Drifts
5. Additional access to Panels from Central Access Drifts

Details of their dimensions are given in Table 8.

Placement Tunnels

The reference CANDU DGR has a total of 124 tunnels in the placement panels. The placement tunnel is composed of a straight portion where the containers are located and a curvilinear portion equal to one quarter of the circumference of a 50 m radius as shown in Figure 8. This curvilnear section provides the access to the placement tunnel from the Perimeter Drifts.

The placement tunnel length for the EPR fuel is similarly calculated as per the reference CANDU DGR design. In the CANDU DGR, 89 boreholes are excavated per tunnel. The EPR design requires 47 boreholes per tunnel to meet the EPR storage capacity.

As per the reference CANDU DGR shown in Figure 9, the straight portion of the placement tunnel consists of the following segments:

1) In the tunnel deadend, a segment of 8.0 m

2) At the tunnel entrance three segments as follows:

    a) length space is provided for the placement of a backfill seal (4.0 m)

    b) an Excavation Damaged Zone (EDZ) seal (6.0 m) and

    c) the half portion of the concrete bulkhead (6.0 m) from where the entrance to the tunnel ends in a 50 m radius circumference corridor.

3) The straight portion of tunnel with the boreholes in its centre line (368 m for EPR fuel when the tunnels are 40 m apart)

Based on these details, the placement tunnel lengths were estimated. In the case of EPR fuel, the tunnel cross section and borehole size follow the Finnish design for EPR fuel. Otherwise, similar designs as the Reference CANDU DGR are used for the seals and the length and shape of the entrance to the placement tunnels.

The overall characteristics and length of the placement tunnels are summarized in Table 7.

Table 7 : DGR Placement Tunnels Characteristics

Fuel Type	Tunnel Separation (m)	No. of Placement Tunnels	Cross-Section Area (m^2)	Tunnel Length (only boreholes section) (m)	Overall Tunnel Length (m)	Total Length of All Placement Tunnels (km)
EPR	25	124	16.2	488	592.5	73.5
EPR	30	124	16.2	428	532.5	66.0
EPR	40	124	16.2	368	472.5	58.6
CANDU	40	124	23.8	369.6	474.1	58.8

Perimeter Tunnels

The perimeter tunnels include the Drift-1 and Drift-2 sections as well the Perimeter X-Cut A, X-Cut B and X-Cut UDF sections. Along the perimeter Drift-1 and Drift-2 sections as shown in Figure 8, the eight 50 m radius curvilinear corridors connecting to the panels and equal to 78.5 m each have been included with these perimeter sections. As a result, the perimeter X-Cut B section and the corresponding sum total of the Perimeter X-Cut UDF and X-cut A sections as per Figure 8, are reduced in their length by 50 m at both ends of the sections as these portions are included in the Perimeter Drift-1 and Drift-2 sections.

Central Access Drifts

The Central Access Drifts are two long tunnels that divide the layout into two halves and join the whole length of the facility connecting the main shaft and the ventilation shafts. They are used for both transferring the UFCs to the placement rooms as well as the equipment for excavation of placement tunnels. The central access drifts have seven small size corridors that allow for communication between them as per the layout shown in Figure 8.

Panel Access X-Cut Drifts

By reference to Figure 8, the Panel Access X-Cut Drifts interconnect the entrace/exit of the placement tunnels to the Perimeter Drifts and the Central Access Drifts.

Additional Access to Panels from Central Access Drifts

Under this grouping of tunnels, the eight curvilinear exits from the Central Access Drifts with a radius of 50 m and length of 78.5 m plus a straight run of 10 m to take account of the 60 m distance separating the Access Drift from the first placement tunnel in the panels are included. The overall dimensions are given in Table 8.

Table 8: Dimensional Characteristics of the Tunnels in the DGR Layouts

Fuel Type	Placement Tunnels Separation (m)	Placement Tunnels (km)	Perimeter Tunnels (m)	Panel Access Drifts (m)	Additional Access to Panels (m)	Central Access Drifts (m)	Overall Boreholes Length (km)
EPR	25	73.5	7180	2985	708	5362	46.4
EPR	30	66.0	6990	3420	708	4882	46.4
EPR	40	58.6	7158	4392	708	4402	46.4
CANDU	40	58.8	7168	4392	708	4418	75.9
Cross-Section Area		EPR ($16.2\ m^2$) CANDU ($23.8\ m^2$)	$25\ m^2$	$25\ m^2$	$25\ m^2$	$35\ m^2$	EPR ($2.41\ m^2$) CANDU ($3.04\ m^2$)

The dimensional characteristics of the various groups of tunnels just described are detailed in Table 8 for the reference CANDU and EPR DGRs under consideration. Based on these values, the total area for the DGR layout can be estimated and it is given in Table 9. The table also shows the DGR area per TWh_e produced. Overall dimensions for the required layout area are also shown.

The results of the analysis indicate that the placement tunnels length and the layout area of a DGR for EPR fuel of 50 MWd/kgU are nearly identical to the reference CANDU DGR when the distance separating the tunnels is 40 m. Smaller surface area can be accomplished by reducing the distance separating the placement tunnels. At a distance of 25 m, a reduction in layout area of about 9% can be realized, however the excavation effort increases significantly since the placement tunnels are longer.

The overall DGR layout is rectangular. The size of the reference CANDU DGR is a rectangle of 1564 x 2001 m^2. The DGR for EPR fuel has nearly identical dimensions for a similar layout. As the distance separating the placement tunnels is decreased, the layout narrows and elongates in the longitudinal direction of the tunnels. So that, the layout area for 25 m tunnel separation becomes a rectangle with sides of 1095 m x 2456 m.

One other important comparative parameter is the surface area required per TWh_e electricity produced (see Table 9). The ratio is in the range 545-624 m^2/TWh_e depending on the layout for both the CANDU and EPR repositories. The value for the reference CANDU repository is 635 m^2/TWh_e. These values are consistent with those reported in 1999 by Allan and Dormuth (see Table 2) which are in the range 500-900 m^2/TWh_e showing that the values in Table 9 are comparable and consistent with those of the previous analyses. Similarly, the nominal average heat flux from emplaced fuel per borehole is in the range 5.7-6.9 W/m^2 for the EPR fuel which compares favorably to the heat flux for CANDU fuel in the reference repository estimated at 7.7 W/m^2 (Table 9). These results indicate that EPR fuel can be stored in a repository as effectively as CANDU fuel.

Table 9: DGR Layout Key Parameters

Fuel Type (Burnup) (MWd/kgU)	Fuel Age (years)	Distance Between Tunnels (m)	Borehole separation (m)	DGR Layout		Max. Avg. Heat flux (W/m^2)	Repository Placement Area (Approx.) (m^2/TWhe)
				(m x m)	Area (m^2)		
EPR 50 MWd/kgU	50.	25	10.6	1095 x 2456	2.69 x 10^6	6.9	545.3
EPR 50 MWd/kgU	50.	30	9.3	1240 x 2216	2.75 x 10^6	6.6	557.5
EPR 50 MWd/kgU	50.	40	8.0	1564 x 1976	3.09 x 10^6	5.7	626.4
CANDU 9.2 MWd/kgU	30	40	4.2	1564 x 2001	3.13 x 10^6	7.7	634.9

7.3 Excavation Volumes

The volume of rock that has to be excavated is of interest because it indicates the effort that will be required to build the repository and its impact on the repository cost. While excavation costs are site dependent and influenced by the quality of rock, costs are generally directly proportional to excavation volume. Hence, an appreciation on the relative contributions to the repository costs can be gained from the values of the excavation volumes for key components of the repository layout.

Table 10 details the volumes of excavated rock for key groupings of tunnels that form the repository layout as detailed in Table 8. However, Table 10 does not include the excavation of the following repository facilities: the additional tunnel work for the Demonstration Facility, the auxilliary facilities by the main service shaft, the main shaft itself, the ventilation shafts and other facilities supporting the transport of the used fuel containers to the placement tunnels. These additional facilities are common to both EPR and CANDU fuel DGRs and are expected to be rather similar in size.

Table 10: EPR CANDU Based DGR Rock Excavation Volumes

Fuel Type (Burnup) (MWd/kgU)	Tunnel Sepa-ration (m)	Excavation Volumes (m^3)				Ratio of Perifery and Access Drifts Tunnels Excavation Volume to Total DGR Excavation Volume (%)
		Boreholes	Placement Tunnels	Access Drifts and Perimeter Tunnels	Total Excavation DGR	
EPR 50 MWd/kgU	25	0.11×10^6	1.30×10^6	0.45×10^6	1.86×10^6	24.2
EPR 50 MWd/kgU	30	0.11×10^6	1.18×10^6	0.43×10^6	1.72×10^6	25.0
EPR 50 MWd/kgU	40	0.11×10^6	1.06×10^6	0.46×10^6	1.63×10^6	28.2
CANDU 9.2 MWd/kgU	40	0.23×10^6	1.40×10^6	0.46×10^6	2.09×10^6	22.0

The results shown in Table 10 are most revealing showing that even though the surface area for the EPR DGR is minimized by laying the placement tunnels closer together, the total rock excavation volume is significantly increased. This is mainly due to the longer length of the placement tunnels as shown in Table 7. The excavation volume for the Perimeter, Access Drifts and boreholes is nearly the same for all three EPR DGRs even though the length of the placement tunnels changed. In fact, from Table 8, the perimeter tunnels size of about 7 km in length is hardly affected by changing the separation distance between the placement tunnels. The excavation volume for the perimeter and access drifts tunnels when combimed together is identical for all the repositories considered, including the reference CANDU DGR. The contribution of this group of tunnels is between 22-28% of the total rock excavated volume for the repository.

With reference to the CANDU repository, the EPR DGR built with a similar layout and identical 40 m separation between the placement tunnels shows a significant smaller excavation volume than the CANDU repository. This difference is about 4.6 x 10^5 m^3 of excavated rock or 22% of the total excavation volume of the CANDU DGR even though both layout, surface area and dimensions are nearly identical between both repositories.

This difference highlights a positive benefit of the EPR DGR over the reference CANDU repository. This is mainly due to a smaller excavation for the EPR fuel boreholes (about half in number) and a near 30% decrease in the excavation of the placement tunnels. The larger excavation volume of the placement tunnels in the reference CANDU repository is due to their larger cross-sectional area (23.8 m^2) over the narrower cross-section (16.2 m^2) of those in the EPR DGR. This difference in tunnel cross-section contributes significantly to the increased rock excavation volume. The tunnel cross-section is dependent on the expected in-situ stresses as well as the mode of placing the container into the borehole. The EPR DGR has a specific emplacement transporter that allows placing the UFC in a slanted position thereby significantly decreasing the tunnel height requirement relative to the container height. In fact, the tunnel height is 0.20 m smaller than the EPR UFC length. If a similar approach and technology were used in the reference CANDU design, the tunnel cross sectional area could be significantly reduced and be made comparable to the EPR tunnel cross sectional area.

Closer scrutiny of the excavation volumes indicate that only two DGR components contribute to the difference in rock excavation volume between the EPR and CANDU repositories: the placement tunnels and the boreholes. Both have total lengths of excavation of comparable value. Table 8 shows the total length to be in the 60-74 km range for the placement tunnels depending on the repository and for the boreholes about 47 km for the EPR fuel and 75 km for the CANDU repository. Of these, the borehole volume for the CANDU repository is about doubled that of the EPR repository. This is not surprising considering that the number of boreholes for the CANDU repository is nearly doubled those of the EPR DGR. The difference in borehole excavation between the CANDU and EPR repositories is 0.12 x 10^6 cubic meters of rock. This is 26% of the total rock excavation difference between the similar EPR and CANDU repositories with placement tunnels separated by 40 m .

In conclusion, the EPR fuel appears to offer certain advantages in the DGR excavation effort when compared to the reference CANDU repository, mainly by achieving a reduction of the excavation requirements. A number of options may be considered to reduce the number of boreholes in the CANDU repository such as increasing the number of bundles per container. The smaller cross-section of the EPR placement tunnels over the reference CANDU tunnels is mainly due to the slenderness of the EPR used fuel container over the CANDU. In the final design, these details could be addressed with the purpose of selecting an optimum cross section. In essence, by judicious design of both DGRs, their main differences leading to higher excavation volumes for the reference CANDU fuel repository could be significantly reduced or eliminated altogether.

In an effort to maximize the efficient use of the rock mass to dissipate the most heat in order to achieve a smaller footprint for the DGR (14% less), the separation between tunnels was reduced from 40 m to 25 m. This effort, though, has the opposite effect on excavation volumes increasing them significantly. The placement tunnels increase their length when the distances separating them become shorter. This is because longer spacing between boreholes is needed to maintain the temperature criteria of 81 C on the used fuel containers surface. The end result is a significant increase of about 14% in the repository rock excavation volume when placement tunnels are separated by 25 m rather than 40 m.

Besides the placement tunnels contributing to the excavation volume increase, the central access drifts contribute to the increase in a minor way reflecting their longer length and consistent with the longer length of the placement tunnels. All the other components do not contribute to the increase, including surprisingly, the perimeter tunnels. This leads to the conclusion that the perimeter of the DGR layout does not change significantly as a result of re-arranging the layout footprint due to the longer placement tunnels.

In closing, similar conclusions can be made for fuel from the Westinghouse AP-1000 reactors. The NDA study (2009) indicated that AP-1000 fuel of average identical burnup to the EPR fuel but with a cooling period of 75 years and a criterion temperature limit of 100^{o}C in a KBS type repository could be emplaced in boreholes located 6.5 m apart. This is a shorter distance than the one considered in this assessment for an EPR DGR, and, therefore, the performance of an AP-1000 fuel DGR is expected to be well within the bounds of this assessment.

8. CONCLUSIONS

The centre-to-centre distance between boreholes in a DGR placing EPR fuel with an average burnup of 50 MWd/kgU was found to be around 8.0 m when the distance between the placement tunnels was 40 m. The borehole separation is about double the distance of 4.2 m estimated for the reference CANDU DGR. The estimated 8.0 m distance between boreholes also compares well to an estimated value of 6.5 m for AP-1000 fuel as reported by the UK NDA. When decreasing the distance between the tunnels to 25 m, the borehole distance increases to 10.6 m.

Based on these estimates, and, on a similar layout of the tunnels as the reference CANDU repository, the size of the underground layout surface area required to place the EPR fuel is similar to the reference CANDU repository when the placement tunnels are 40 m apart as required in the reference CANDU repository. Smaller layout surface areas amounting to a reduction of up to 14% over the reference CANDU repository can be accomplished by reducing to 25 m the distance between the placement tunnels but still maintaining the used fuel containers surface temperature at 81 ^{o}C as per the reference CANDU repository. However, the rock excavation volumes substantially increase.

In contrast, the rock excavation volumes show that the layout for EPR fuel with centre-to-centre tunnel distances of 40 m offer the smaller excavation volume of all the cases studied. A reduction of up to 22% of the excavation requirements over the reference CANDU repository might be achievable. The excavation volume for an EPR DGR with tunnel distances of 25 m shows a nearly identical excavation volume as the reference CANDU repository even though its layout surface area is about 30% less than the reference CANDU repository.

In all instances, the surface area per TWh_e generated is of the order of 500-600 m^2/TWh_e. These values are consistent with earlier reported literature values for similar repositories. In conclusion, the layout of the reference CANDU repository is not significantly affected by placing high burnup EPR fuel.

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APPENDIX

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A.1 ESTIMATING THE DISTANCE OF SEPARATION BETWEEN BOREHOLES

An analytical approach to the estimation of the distance of separation of the placement boreholes in the DGR is done by approximating the used fuel containers as finite line heat sources and solving the resulting heat transfer model. This method of estimating the temperature profiles in the DGR was first used by Chan and co-workers (1978, 1980) while studying the STRIPA Heater Experiment conducted by the SKB in Sweden in the late 1970's.

Modelling the container as linear heat sources allows for the solution of the thermal model analytically by means of Green's functions. When dealing with an array of sources, the solutions from the individual heat sources can be superimposed to calculate the overall temperature profile. Bäckblom (1978), in particular, formulated the following equation for a constant heat source to estimate the temperature profile of the rock mass along the midplane of a container:

$$\Delta T(r,0,t) = \frac{Q_l}{2\pi\kappa}\int_0^b \frac{erfc\left[\left(\frac{r^2+z'^2}{4\kappa t}\right)^{1/2}\right]}{\left(r^2+z'^2\right)^{1/2}}\,dz' \quad \text{.........(1)}$$

where

ΔT = Temperature increase

Q_l = Heat generation rate per unit length per unit time (W/m)

r = radius from centreline of the container

$\boldsymbol{\kappa}$ = k/ρc = Thermal diffusivity where k is the thermal conductivity, ρ is the density and c is the heat capacity of the rock

b = the mid-height of the container (acting as a finite length linear heat source)

Since the heat of decay changes slowly over time, this equation can be used to advantage to scope the allowable distance of separation between the containers by assuming the heat transfer is in a quasi-steady state. It was also used as a quick check on the temperatures extrapolated from the work of Ikonen. More recently, Hautojarvi and Ikonen have added to this work by extending this approach in considerable detail to the analysis of various Finnish proposals for a DGR to emplace high burnup fuel including EPR fuel (Ikonen, 2005, 2009, Raiko, 2005). In particular, Ikonen used the following solution developed by Hautojarvi for a used fuel container with a decaying heat source as it is the case with the stored fuel:

$$T(x,y,z,tmax) = \frac{1/H}{4\pi\kappa\rho c}\int_0^{tmax}\frac{P(t)}{(tmax-t)}\,e^{-\frac{x^2+y^2}{4\,\kappa\,(tmax-t)}}$$

$$\cdot\frac{1}{2}\left\{erf\left[\frac{1}{2\sqrt{\kappa(tmax-t)}}\left(\frac{H}{2}+z\right)\right]+erf\left[\frac{1}{2\sqrt{\kappa\,(tmax-t)}}\left(\frac{H}{2}-z\right)\right]\right\}dt$$

…equation (2)

where H is the height of the line heat source (note that in the model this is given as the effective height of the container as determined by Ikonen (2009) and equals the height of the container plus the container radius).

P(t) is the power of the container due to the heat of decay of the fuel stored in the used fuel container given in Watts.

κ, ρ and c are as defined above for equation (1) and t_{max} is the time for which the temperature is determined and *t* is the integration variable.

Of particular importance is the dimensionless form of equation (1) and (2). The development is presented by Chan et al, 1980, who showed that for a comparison of the quasi-steady state temperature rise between containers of different heat source strength or power and different rock type, the temperature rise is:

1. inversely proportional to the thermal conductivity of the rock.

2. directly proportional to the power per unit length of the heat source.

Equation (2) can be used to estimate the temperature profile in the rock up to the boundary with the engineered barriers. Then, the temperature profile across the barriers is found in the usual way for heat transfer in a quasi-steady state for a cylindrical geometry with multilayered thermal barriers. Details of this analysis can be found in Ikonen (2005 and 2009) for the Finnish concept of the enginneered barriers. In their concept, an air filled gap exists between the container surface and the bentonite layer. Heat transfer in the gap is mainly by radiation. On the outer face of the bentonite layer, another gap exists between the bentonite and the rock. This gap, however, is filled with water and the heat transfer is mainly by conduction. At a difference with the Finnish concept, the CANDU engineered barrier concept has the two gaps filled with bentonite pellets thus resulting in a conductive multilayered barrier through which heat is transferred.