Development of the Canadian Used Fuel Repository Engineered Barrier System

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The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally-approved plan for the safe long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

In implementing APM, the NWMO is committed to ensure consistency with international best practices in the development of its repository system, including any advances in technology.

In 2012, the NWMO undertook an optimization study to look at both the design and manufacture of its engineered barriers. This study looked at current technologies for the design and manufacture of used fuel containers, placement technologies, repository design, and buffer and sealing systems, while taking into consideration the state of the art worldwide in repository design and acceptance.

The result of that study is the current Canadian engineered barrier system, consisting of a 2.7 tonne used fuel container with a carbon-steel core, copper-coated surface and welded spherical heads. The used fuel container is encapsulated in a bentonite buffer box at the surface and then transferred underground. Once underground, the used fuel is placed into a repository room which is cut into the rock using traditional drill-and-blast technologies.

This paper explains the logic for the selection of the container and sealing system design and the development of innovative technologies for their manufacture including the use of laser welding, cold spray and pulsed-electrodeposition copper coating for the manufacture of the used fuel container, isostatic presses for the production of the one-piece bentonite blocks, and slip-skid technologies for placement into the repository.

I. Introduction:

In 2002, the Government of Canada passed the Nuclear Fuel Waste Act[1], resulting in the creation of the Nuclear Waste Management Organization (NWMO) to develop and implement a plan for the long-term care of the nation's used nuclear fuel. This paper describes the Canadian engineered barrier system design, explain how we came to chose each of the features of the system and show how all parts of the system are integrated.

The Canadian deep geological repository engineered barrier system consists of 3 elements:

- Used fuel container
- Buffer
- Emplacement equipment

These 3 elements are designed to fully integrate with the Canadian repository system.

II. Container:

The Canadian used fuel container is smaller and lighter when compared to other vessels used around the world. The design selected was based on the findings of a detailed sizing study of 20 different alternatives (size/geometry/capacity) which considered engineering design, vessel manufacturability/automation, encapsulation plant operations and emplacement considerations. It weighs 2.7 tonnes when filled with used fuel and is 2.5 metres long.

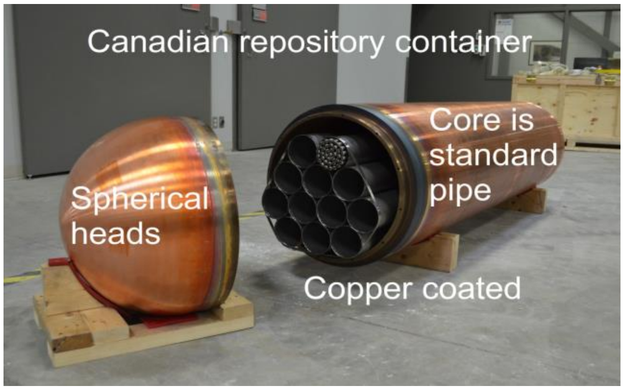

Figure 1 Canadian repository container

The Canadian container has 4 unique design features:

1. Cylindrical Shell
2. Spherical Heads
3. Welded Construction
4. Copper Coated

II.A. Cylindrical Shell:

In developing the Canadian design we were looking for a container that could be easily emplaced with simple equipment. In order to achieve this we undertook a study to determine the most appropriate size for our used fuel container. That work resulted in the selection of a container with a cylindrical shell made of 22 inch diameter schedule 140 pipe. The material is SA 106 Gr.C. This carbon steel pipe is both readily available from multiple suppliers and is prequalified to meet the requirements of the ASME code. By using this standard sized pipe we avoid the need for custom forgings which can have long delivery times and cost implications.

The steel shell of the used fuel container must support the large glacial loads which can occur within a Canadian repository. We chose a grade of standard ASME P1 Gr. 2 pressure vessel steel because of the combination of strength, ductility and fracture toughness properties suitable for the functional design requirements of the vessel. This includes the ability to withstand any irregular loads which may occur over the million-year lifetime of the repository. We have extensive experience of successful nuclear fabrication using this material and its structural and corrosion performance are well understood and amenable to a repository environment.

II.B. Spherical Heads :

A used fuel container in a Canadian repository will be subjected to large hydrostatic loads (up to 45 MPa, Ref 2). While these hydrostatic loads act on the outside of the vessel it is still classified as a pressure vessel. It is well known that the best geometrical shape for withstanding these external pressures is a sphere. For that reason, the heads on the Canadian used fuel container are spherically shaped. The spherical heads are fabricated (hot-formed) from SA-516 gr. 70 plate; the material falls under the same ASME classification as the SA-106 Gr. C shell.

The spherical shape ensures that there are minimal tensile stresses under the compressive hydrostatic load in the repository. When designing a vessel for a lifetime of hundreds of thousands of years, tensile stresses within the container should be avoided. Figure 2 contrasts the stress distribution that occurs within a used fuel container with flat heads and with spherical heads. There are significant areas of tensile stress within the flat headed container while the spherically headed container has minimal tensile stress. Also, spherical heads result in uniform stress throughout both the head and the cylindrical shell of the container.

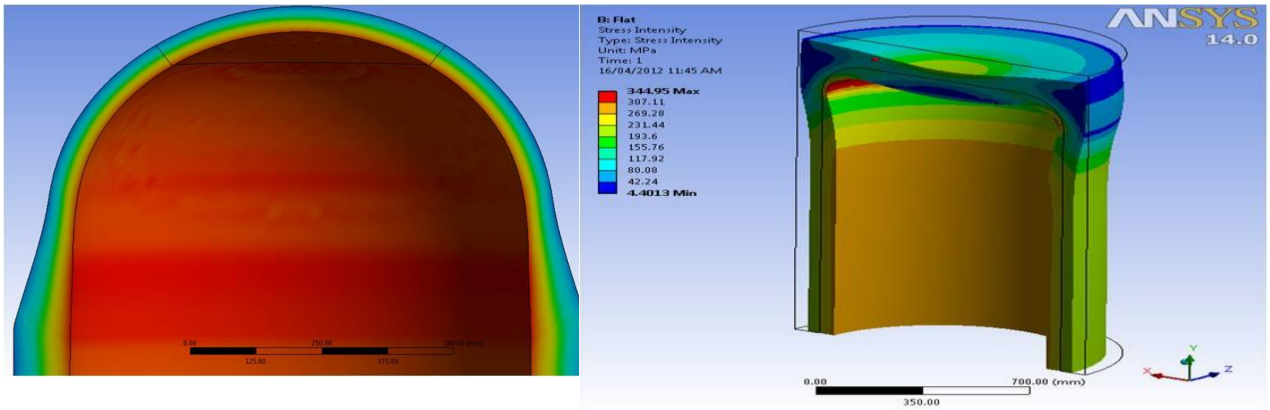

Figure 2 Stresses in a spherical vs. a flat head

Furthermore, the steel shell will be covered with copper. Copper under tensile load creeps over time. The time frames involved in a deep geological repository are sufficiently long that the creep behaviour of the copper shell is unpredictable. By using a spherical head, the Canadian design avoids tensile stresses in the copper layer and hence eliminates any concern of creep failure of the copper.

II.C. Welded Construction:

The used fuel container is intended to isolate and contain the used nuclear fuel for as long as it remains hazardous. The use of a seal weld is the best long term construction method to achieve this. A concern with a closure weld is the need to post weld heat treat in a hot cell environment. As the used fuel will need to be packed before the closure weld is made any post weld heat treatment will need to be done with used fuel inside the container. The Canadian repository requires that the used fuel be retrievable. As such, damage to the used fuel from post weld heat treatment is unacceptable.

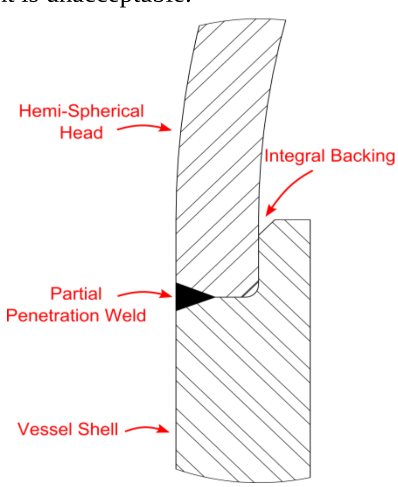

Figure 3 Partial penetration weld design

To support the same hydrostatic pressure, a sphere can be significantly thinner than a cylinder. The Canadian used fuel container takes advantage of this natural effect to support the structure avoiding the need for a full penetration weld. Figure 3 illustrates the design of the Canadian partial penetration weld which uses the integral support ring from the thicker cylindrical shell to carry the hoop load associated with the spherical head. This partial penetration weld does not need post weld heat treatment.

NWMO investigated a number of welding processes and selected laser weld with a 450^{o} C preheat as the reference welding procedure for the partial penetration seal weld of the Canadian used fuel container. This welding process has produced a fully ductile weld with high Charpy impact toughness. No evidence of martensite within the weld or heat affected zone was found by metallography and hardness measurements (<240 HVN). Further, residual stress in the weld is less than 1/3 of yield strength of the SA-516 Gr 70 materials.

Figure 4 shows a compressed weld ring. The ring was manufactured using our partial penetration weld procedure. We were able to fully crush the ring with no weld cracking.

Figure 4 Weld ring crush test

II.D. Copper Coating:

The Canadian used fuel container has a steel shell to provide the strength needed to withstand the repository loads. Copper is coated onto the outside of the steel to provide corrosion protection. Copper is selected for its excellent corrosion performance in a repository environment, particularly as it is not subject to pitting in this anaerobic environment.

While we do not expect the copper to undergo any corrosion after emplacement, we selected the coating thickness after looking at all possible corrosion mechanisms. Based on this analysis the worst case scenario would involve an average of 1.25 mm of corrosion over 1 million years[3]. To allow a safety factor, the Canadian used fuel container will have a coating of 3 mm of copper which is bonded directly to the steel core.

By using copper coating the NWMO avoids problems associated with potential creep failure. Strains on the copper coating are less than 1 percent which is well below the creep failure limit for raw copper. To achieve our copper coating requirements the bulk assembly is coated in the container factory using electro-deposition. After welding in the hot cell, the weld zone is coated using cold spray. The following photographs show a container after welding but before coating and a final completed container with cold spray copper coating over the closure weld (figure 5).

Figure 5 Welded container

III. Buffer:

Experimental results have shown that the use of highly compacted bentonite with a dry density in excess of 1.6 g/cm^3 will inhibit microbial activity in a Canadian geosphere[4]. To achieve this, the container will be placed inside a bentonite buffer box as illustrated in figure 6. The buffer box will be encapsulated in a sheet metal shell (1 mm thick) to prevent damage during transfer to the underground. The buffer box shell has a limited amount of steel (less than 50 kg) to avoid damage to the rock due to hydrogen generation during corrosion.

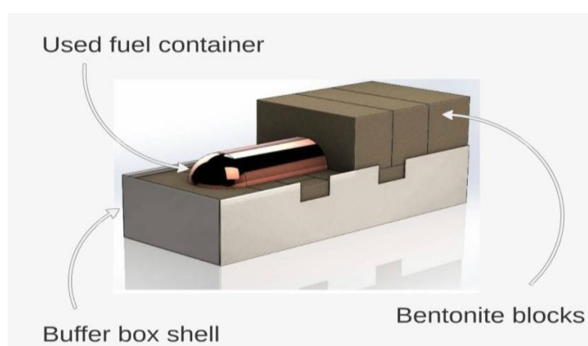

Figure 6 Buffer box

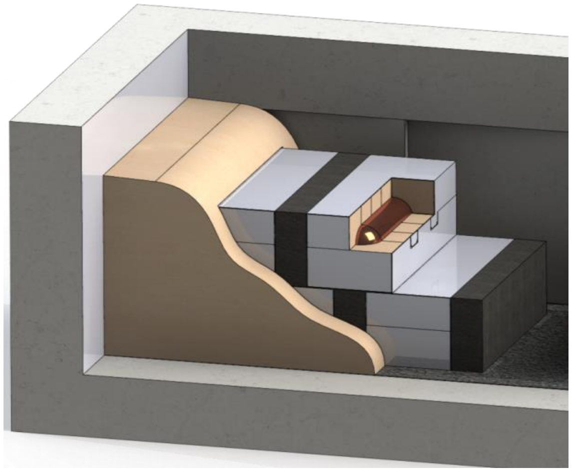

Figure 7 Buffer box emplacement

By placing the used fuel container into the buffer box at the surface the bentonite will protect the copper during transport. As shown in brown in figure 7, highly compacted bentonite gapfill will be used in the spaces around the outside of the buffer box to seal any spaces between the buffer box and the rock.

Another component of the buffer box emplacement system is the spacer blocks. As shown in black in figure 7, between each buffer box is a spacer block. This spacer block is to allow for additional heat transfer area from the used fuel container to the surrounding rock. The dimensions of this spacer block can be altered depending on the thermal conductivity of the rock surrounding the emplacement room. The size of the spacer block is set to limit the maximum temperature at the surface of the container to 100^{o}C.

IV. Emplacement:

As has been stated previously one of the intentions of the Canadian program is to develop a system whereby used fuel containers can be emplaced using simple standard equipment. Figure 8 shows the emplacement technology which has been developed.

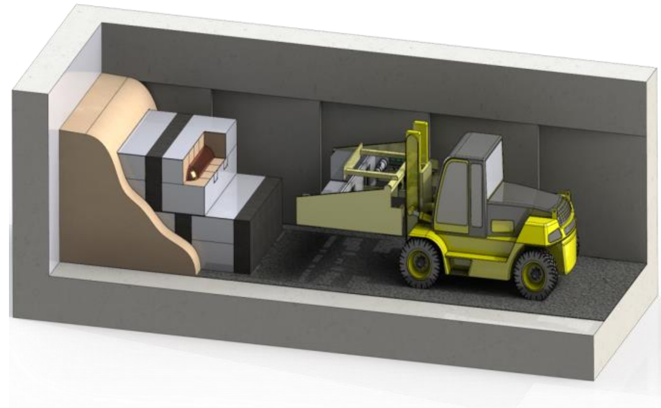

Figure 8 Canadian slip skid emplacement system

The emplacement room uses standard drill and blast excavation methods. There is no sophisticated boring or tight dimensional tolerance necessary. The emplacement is undertaken with a remotely operated wheeled vehicle and buffer boxes are stacked using slip skid technology to avoid the need to leave any emplacement skids inside of the room. Buffer boxes are emplaced 2 high in a room which has been excavated to 3 metres wide by 2 metres high. As the excavation equipment backs out of the room gapfill pellets are placed into the volume between the wall and the buffer boxes.

The room is designed so that keyed seals are placed every 100 metres along the length of the emplacement room.

V. Progress to date and plan moving forward:

In 2014 NWMO manufactured its first used fuel container. In 2015 and 2016 this container design will undergo a series of complete pressure tests well beyond the design load of 45 MPa. This will verify the performance of the container. In 2016 and 2017, we will manufacture 20 to 30 containers in a production environment to prove the repeatability in manufacturing the container.

In 2014 NWMO manufactured its first buffer box using small bentonite bricks. In 2015 we will upgrade this to use large blocks (2 per buffer box).

NWMO is not developing any gap fill material. For this we are relying on work done by NAGRA, our Swiss counterpart who have an excellent gap fill development program. In 2015 we will develop the material handling equipment to place the gap fill around the buffer box.

We are currently building an emplacement room that will be used to complete our emplacement trials. By the end of 2015 we will have completed this room and will have demonstrated the emplacement of our buffer boxes and gap fill material.

In 2015 we will complete our prototype slip skid machine and in 2016 we will automate it. This will be ready for our emplacement demonstrations in 2017 and 2018. By the end of 2018 we expect to have completed the demonstration of our engineered barrier system and be ready to begin preparing our licence submission.

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