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EVOLUTION OF THE DESIGN OF THE ENGINEERED BARRIER SYSTEM FOR THE LONG TERM MANAGEMENT OF CANDU® FUEL

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Abstract

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

Consistent with technology advancements, the engineered barrier design hasevolved, but the original technical solution defined in the late 1980s remainsthe preferred technical solution; containerization of used nuclear fuel intolong lived metallic containers encased in bentonite with the engineered barrierisolated from the biosphere in an engineered structure deep underground.

The current evolution of the Used Fuel Container (UFC) engineered barrier utilizes commercial steelpipe with spherical heads. Hybrid laser arc welding affixes the heads to thepipe. The entire UFC is copper coated, prior to loading and final assembly;excepting a small width required to permit welding of the final head after allfuel is loaded. Cold spray is used to apply the copper coating over the weldarea. The final assembled UFC is placed in a highly compacted bentonite block,assembled from two pressed blocks forming a rectangular package transferredunderground. It is placed in an emplacement room using slip skid technology todeposit the assembly in a one wide by two high assembly arrangement. Highlycompacted bentonite spacer blocks provide the require assembly offset tocontrol peak UFC surface temperature. Each room is filled in a retreating
manner.

Keywords: Deep Geological Repository, Evolution, Bentonite,

1. Introduction

The Nuclear Fuel Waste Act[1] passed by the government of Canada in 2002 resulted in the creation of the Nuclear Waste Management Organization (NWMO) to develop and implement a plan for the long-term care of Canada's used nuclear fuel. This paper will review the progression of the technology and systems designed to safely contain and isolate used nuclear fuel from people and the environment. While the general approach identified in the 1980's and adopted by most nuclear countries for management of their nuclear fuel waste remains constant, significant progress has been made in refining and demonstrating the technologies. This paper will review the original technology concepts identified in the 1980's and discuss their evolution to the current reference design adopted by the NWMO.

The Canadian deep geological repository technology demonstration program is focusing on the following three elements for physical demonstration:

- Used fuel container
- Buffer
- Emplacement equipment

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

2. Background

2.1 Original Design Concept

The goal of any Deep Geological Repository System is Containment and Isolation of the used nuclear fuel from the natural environment. While the Canadian concepts have evolved over the years, the same basic design attributes identified in the 80's remain in place today, that is:

- Containment of used fuel in a durable metal container
- Provide an environment for the container that ensures long life
- Isolate the container from ground waters and the natural environment by constructing an engineered underground facility deep in stable rock to permanently house the used nuclear fuel hazard decays with time

The original design concepts adopted a large used fuel bundle capacity double walled vessel fabricated with an inner steel shell. The inner steel shell is designed to resistexternally applied structural loads imparted from sealing system swelling pressures and glacial loads while an exterior copper shell provides corrosion protection. Each Used Fuel Container would be emplaced in boreholes and encased in highly compacted bentonite rings. All emplacement rooms would be filled with highly compacted bentonite. Canada, Sweden and Finland advanced this concept through the 90s and early into the 2000s. Sweden and Finland have this original design concept to their regulatory authorities to obtain approval for construction.

It is worth mentioning that there is an example in nature where natural occurring uranium ore was covered with a clay cap near significant water resources, and there were no traces of the uranium beyond the deposit.

2.2 Evolution of the Concept

Most European countries use Boiling Water Reactors and Pressurized Water Reactors. The fuel assemblies used in these reactors can measure in excess of four metres in length. To minimize the number of UFCs required, fuel assemblies will be consolidated into large diameter, long length UFCs. While there is attraction in utilizing large containers to economize on the number of vessels required and minimizing the total number of handling requirements, it does constrain working with specific manufacturing processes. Forgings are required for the steel inner vessel and the copper outer vessel. Large specialized presses are needed to press the container shapes and the bentonite blocks. Currently, there are no more than a handful of suppliers capable of producing these components.

With the exception of a very small inventory of research reactor fuel, Canada's used fuel inventory is CANDU® fuel. The small dimensions of CANDU® fuel bundles provide options for DGR implementation in Canada. Technology evolution over the last decade in coatings, computer modeling and robotics have provided the NWMO an opportunity to refine the DGR technology while remaining faithful to the original concept as advanced by Sweden and Finland.

3. Fast Forward 2016: Current Design Concept

3.1 Container

The Canadian used fuel container is smaller and lighter when compared to other vessels used internationally. The NWMO design evolution was based on the findings of a detailed sizing study of 20 different alternatives (size/geometry/capacity). The study balanced engineering design, vessel manufacturability/automation, encapsulation plant operations and emplacement considerations. The recommended vessel weighs 2.7 tonnes when filled with used fuel and is 2.5 metres long. In contrast, the long length, large diameter double vessel adopted in Europe weighs around 25 tonnes when filled with fuel[3].

The Canadian container has 4 unique design features:

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

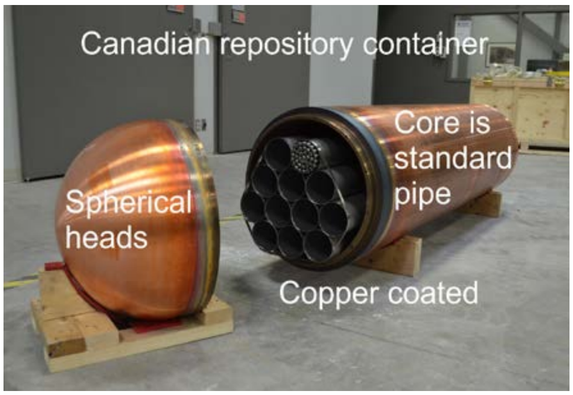

Figure 1 Canadian repository container

3.2 Cylindrical Shell

In developing the Canadian design we were looking for a container that could be emplaced with simple equipment. A study was undertaken to determine the most appropriate size for our used fuel container given the opportunity presented with our small fuel bundles. A cylindrical shell made of 22 inch diameter schedule 140 pipe was selected. The material chosen for fabrication 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. Adopting standardized pipe eliminates 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. Standard ASME P1 Gr. 2 pressure vessel steel was selected because of its 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. The industry has extensive experience of successful nuclear fabrication using this material and its structural and corrosion performance are well understood and amenable to a repository environment.

3.3 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. Taking advantage of this feature, 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.

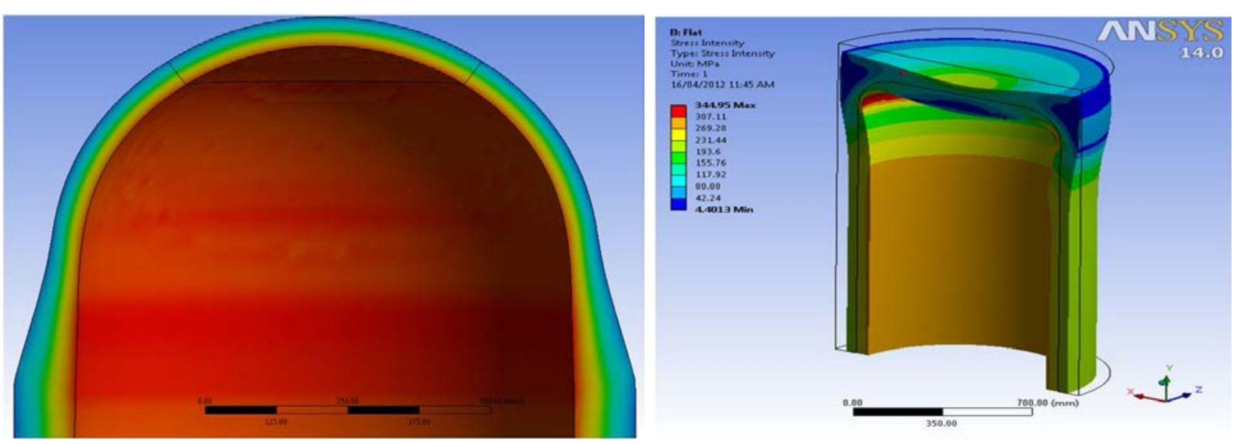

Figure 2 Stresses in a spherical vs. a flat head

3.4 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 treatment will not be acceptable and a process solution not requiring post weld heat treatment is preferable.

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.

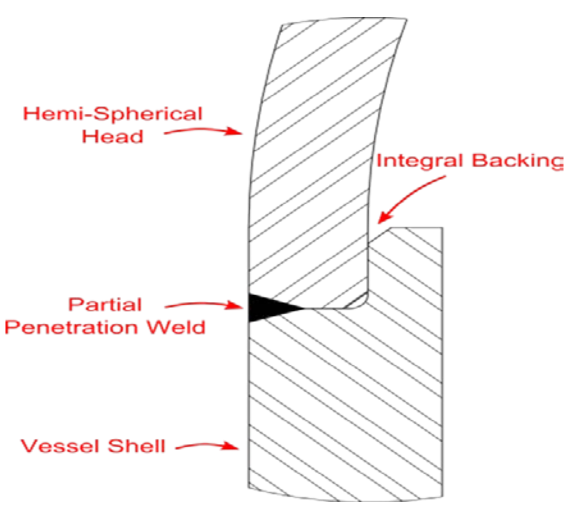

Figure 3 Partial penetration weld designFigure 4 Weld ring crush test

3.5 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 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

3.6 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.

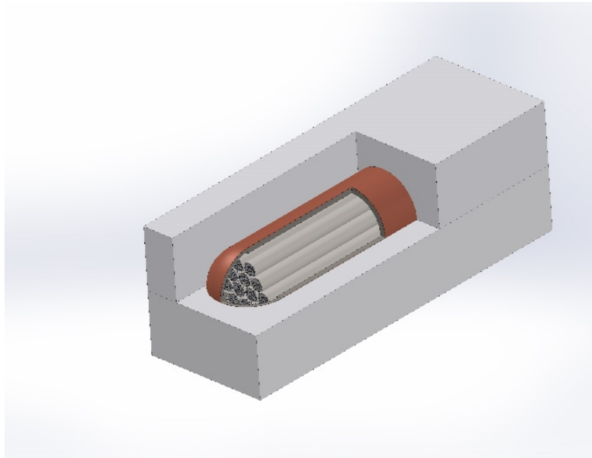

Figure 6 Buffer Box

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 below 100^oC.

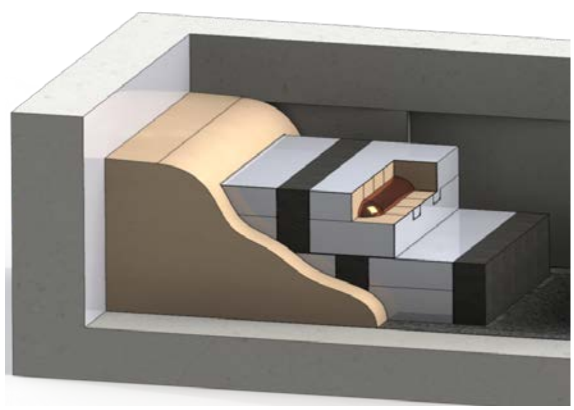

Figure 7 Emplacement Room Configuration

4. 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.

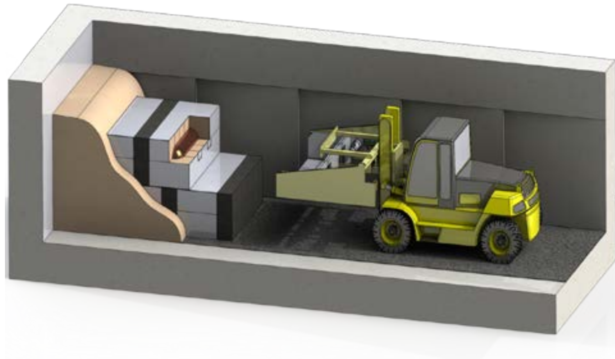

Figure 8 Buffer box emplacement

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.

5. Progress to Date

There has been significant progress on the basic conceptual building blocks of the technology. The first full size UFC was fabricated in 2014. An uncoated UFC was successfully pressure tested in 2015 and demonstrated that the finite element computer model predicted accurately the performance of the UFC under load. Figure 9 shows a UFC being lowered into the isostatic pressure chamber prior to load testing.

Figure 9: UFC Pressure Test

The copper coating program has demonstrated successful electrodeposition of a number of heads and lower assembles. By the end of 2016, a UFC shall be fully fabricated with the electrodeposited copper for the heads and main body and cold spray over the weld area as required for the proposed coating process.

Figure 10 illustrates a lower assembly with electrodeposited copper.

Figure 10: Electrodeposited Copper Lower Assembly

The highly compacted bentonite program has successfully fabricated 3 full size blocks of HCB. This represented a significant step forward for us by demonstrating that a buffer box can be fabricated with only two large blocks. The required uniform dry densities were exceeded, providing margin in the design. Figure 10 illustrates a full size block as squared.

Figure 10: Full Size Block

The gapfill demonstration program has advanced with production of gapfill as well as design / build of a gap fill delivery auger. Initial trials demonstrated that the auger is capable of forcing the gap fill into irregularities as necessary to fill cracks and voids in the emplacement room. The gapfill test auger is shown in Figure 11.

Figure 11: Gapfill Auger Delivery Platform

The slip skid conceptual equipment has been successfully designed and fabricated. Demonstration work to develop procedures and verify technology performance will begin in the summer of 2016 and continue into 2017. Figure 12 shows the conceptual platform for demonstration of the basic slip skid technology.

Figure 12: Slip Skid Frame

Through 2016 / 2017, as though the basic technologies are demonstrated and matured, refinements will be made in preparation of serial demonstration work to occur 2018/2019.

6. References

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