FULL-SCALE EXTERNAL PRESSURE TEST OF USED NUCLEAR FUEL CONTAINER FOR DEEP GEOLOGICAL DISPOSAL

C. Boyle[1], S. A. Meguid[2]
[1] Nuclear Waste Management Organization, Toronto, Ontario, Canada
[2] University of Toronto, Toronto, Ontario, Canada
[1] cboyle@nwmo.ca, [2] meguid@mie.utoronto.ca

Abstract

Many countries around the world are pursuing the implementation of a Deep Geological Repository (DGR) for the long-term storage of used nuclear fuel and high-level waste. For direct disposal of used fuel, the general concept consists of re-packing the fuel into long-lived Used Fuel Containers or Canisters (UFC). These containers are placed deep underground, typically over 400m in depth, and surrounded with clay sealing materials.

Structurally, the container is designed to withstand the postulated loadings in the DGR including clay buffer swelling pressures, pore water pressures, and future glacial loading events. As a conservative worst case scenario, a maximum uniform external pressure of 45MPa is assumed from a combination of buffer swelling, fully saturated rock to DGR depths, and the hydrostatic head from a 3000m thick glacier directly over the repository.

To ensure the container can withstand this extreme loading, a Finite Element Model (FEM) that can accurately predict the structural response of the container, including the non-linear buckling collapse load, was developed. An external pressure test of prototype container was performed at Penn State's Advanced Research Laboratory High Pressure Test Facility to validate the model and container fabrication techniques. The container collapsed as predicted at approximately 57MPa. The validated model can now be used to predict the behaviour of the container in the DGR under normal evolution and beyond design basis loading scenarios. In addition, prototype fabrication including container machining and welding have been verified.

1. Introduction

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM) [1] for the long-term care of Canada's used nuclear fuel. The program's objective is to create a socially acceptable, environmentally responsible, and economically feasible used fuel solution. The technical solution to be implemented by the APM program is the creation of a Deep Geological Repository (DGR). The used nuclear fuel is encapsulated in long-lived *Used Fuel Containers* (UFC), then emplaced at a reference depth of 500m underground in a suitable rock formation, and surrounded with bentonite clay, as shown in Figure 1. The DGR method is consistent with international best practices as demonstrated by it being the approach adopted by many nuclear producing countries around the world [2, 3, 4, 5].

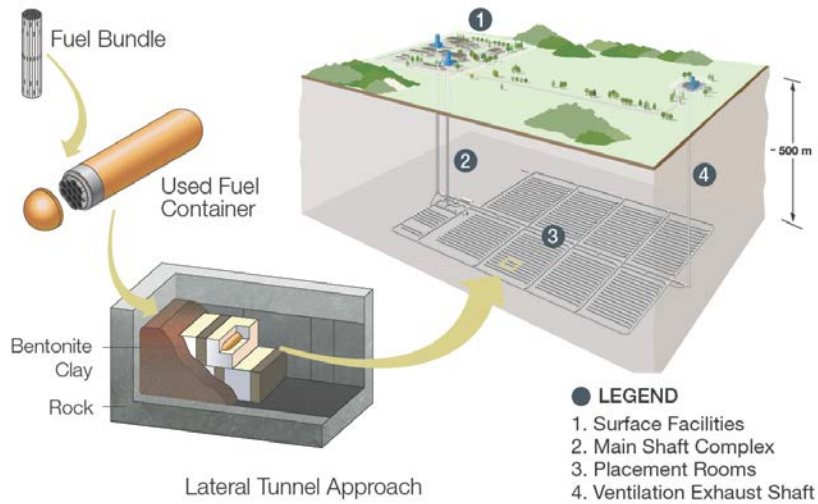

Figure 1 NWMO Deep Geological Repository (DGR) Concept

A major engineered component of DGR design is the *Used Fuel Container* (UFC). The UFC is steel/copper vessel, in which the used fuel is packaged before final underground emplacement. The UFC is designed and fabricated to ensure performance for its intended safety function: containment and isolation of the fuel for several thousand years. The NWMO has developed a container specifically designed for CANDU fuel, shown in Figure 2, with several novel design features:

1. Constructed using standard nuclear pressure vessel grade materials and sizes
2. Hemi-spherical heads for uniform distribution of external pressure loads
3. Smaller sized container, weighing less than 3 tonnes when loaded with fuel
4. Copper coating corrosion barrier integrally bonded to structural steel container
5. Partial penetration Hybrid Laser Arc Weld (HLAW) for container closure

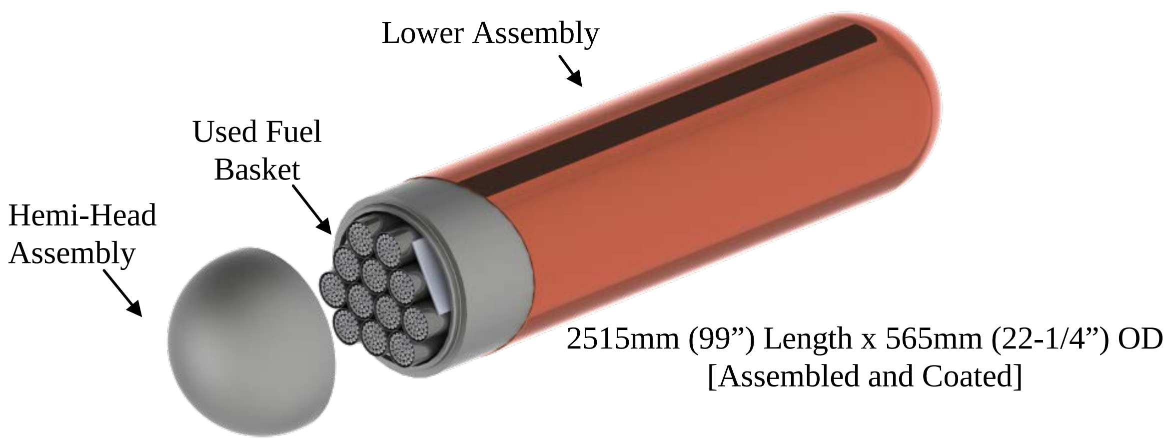

Figure 2 NWMO’s Mark II Used Fuel Container

To achieve its safety function, the UFC needs to maintain structural integrity under the expected loadings in the repository. These loads will be site specific depending on the geological characteristics of the location; therefore, the NWMO currently assumes the bounding (worst case) values for the two primary loading conditions know as normal evolution and glacial loading.

- Normal evolution: After DGR closure, water is expected to ingress into the tunnels and around the container. The initially dry bentonite clay surrounding the container absorbs this water and swells. Due to the confined tunnel space, the buffer swelling exerts a pressure on the container. The hard-rock excavated tunnels support the weight of the above geosphere; therefore, negligible lithostatic loads are imposed on the container directly. However, the rock can hold groundwater in its cavities or pores and exert a "pore water pressure". Conservatively, we assume full hydrostatic water-head pressure equivalent to the depth of the repository. In addition, this is conservatively assumed to be 100% additive to the buffer swelling load. The maximum external pressure resulting from the combination of hydrostatic head and buffer swelling is approximately 15MPa.

- Glacial loading: In 50,000 - 100,000 years, it is postulated that another ice age will occur across Canada, as a result, a 3000m thick glacier could develop over the repository. This ice sheet would exert some amount of mechanical load onto the repository; in addition, the ground above the repository may fully saturate with water during advance / retreat of the melting glacier. The theoretical maximum load that could be applied to the container occurs if a melt-water column, assumed to pierce through the full height of the frozen glacier, connects to the fully saturated groundwater and penetrates continuously to full repository depth. Additionally, it is assumed that this hydrostatic pressure adds fully to the swelling pressure of the bentonite clay, something that has been shown experimentally to not be true [6]. The resulting pressure is 45MPa; approximately equivalent to 4,500m of water depth - the height of 8 CN towers. While this is an extremely unlikely scenario, it serves as an ultra-conservative bounding load to assess the container's structural performance.

The UFC was designed following the intent of international nuclear codes and standards, as well as, industry best practice. Detailed analytical and numerical analysis was employed to ensure the UFC maintains its integrity under these loads. Specifically, we created a computational Mechanical Integrity Model (MIM) that can calculate the container response under any loading scenario. This model has previously been validated using small-scale experiments [7]; however, due to the safety significance of the UFC, we have elected to perform a full-scale validation via an external pressure test of a prototype Mark 2 UFC.

This paper will present the methodology and results of an experimental full-scale external pressure test on a prototype Mark 2 Used Fuel Container. The test evaluates the container for the normal and glacial loading scenarios, followed by a beyond design-basis test to failure. The experimental results will be compared to the computational model's predicted container response.

2. Method

2.1 Full-scale External Pressure Test Experiment

2.1.1 Pressure Testing Equipment

The NWMO performed that testing at the Penn State Advanced Research Laboratory (ARL) High Pressure Test Facility (HPTF). It is one of the few facilities in North America that can test a container of this size at these pressures. The large pressure vessel has an internal working diametre of 1.524m

(60”) and length of 4.19m (165”). The maximum operating pressure is 110MPa equivalent to the pressures at the deepest part of the ocean – the Mariana Trench. The vessel itself weighs 140 metric tons and is fabricated from high strength steel with 254mm thick walls (10”) and a lid that is almost a metre thick. The working fluid for this test is water.

2.1.2 Prototype Container Fabrication and Preparation

For the first test, a steel-only prototype container was fabricated. All structural rigidity originates from the steel – little support is added by the copper coating and no support is added by the fuel basket or fuel itself. As the pressure increases, the container deforms very little (i.e. <3mm on the diametre) until a critical pressure is reached. At this pressure, the container is said to “buckle”, rapidly collapsing into a flattened shape. This large deformation occurs almost instantaneously. This large deformation could cause substantial damage to Penn State’s pressure vessel system components (e.g. pumps, piping, etc.) due to cavitation and shockwaves generation. To prevent this, we designed a fully-dense inner vessel to arrest the collapse. The inner vessel is fabricated from 3/8” (~9.5mm) thick steel pipe and filled with concrete. The diametre of the inner vessel is 17” (~432mm), meaning that the container can collapse diametrically by ~1.25” (~32mm) after buckling. The inner vessel is free floating, does not provide any structural support prior to collapse, or affect the buckling load validation.

Figure 3 NWMO’s Mark II Used Fuel Container

2.1.3 Container Handling

To allow manipulation into Penn State’s ARL’s HPTF’s vertically oriented pressure vessel, a custom designed transportation and handling fixture was developed for the Mark 2 UFC. The fixture has to be able to transport the container without damage, free-stand vertically, and withstand pressures up to 70MPa. In addition, it has to impart minimal loads on the container and allow collapse without damage. To achieve this a steel frame with four removable cross-bars, three on the top and one on the bottom, was constructed. All cross-bars are installed for shipping of the UFC. Prior to testing the upper and lower crossbars at the center of the fixture are removed. These are removed because the computer modeling predicts that buckling will initiate at the mid-shell. Tight confinement in this area could lead to damage of the fixture and compromise lifting capacity.

Figure 4 Used Fuel Container fixture configured for testing

2.1.4 Container Strain Gauge

Three different types of strain gauges were installed on the prototype container including linear, bi-axial, and tri-axial. A total of 24 gauges were installed with the objective to monitor the strain as a function of external pressure prior to buckling and compare those to the computer modeling. The gauges were installed near the weld zones, quarter length of shell, middle of shell, and near the apex of the hemi-head.

Installation and continued function of strain gauges in a submerged, high pressure water environment is incredibly challenging. It requires a technique called "potting". The strain gauge, portion of wire, and surrounding substrate are coated in a solid rubber-like compound. The compound protects the strain gauges from the water / pressure; however, ensuring adhesion to both the substrate (i.e. container surface) and wire is difficult. Any opening, disbond, or low adhesion will fail under increasing pressure and allow water to penetrate in. A pinhole in any part of the wire casing will also lead to water intrusion. Strain gauge installation followed the procedure as recommended by the manufacturer.

The potted strain gauges and water proof strain gauge through-wall connectors are shown in Figure 4.

Figure 5 Strain gauges potted onto the Mark II Used Fuel Container prototype with water proof through-wall connectors

2.1.5 Container Inspection

Visual and Non-Destructive Examination (NDE) were completed prior to and after each pressure test stage as outlined below:

- All exposed areas of the container were visually examined for cracks or noticeable deformations. The container fixture and strain gauge wiring were also examined for signs of damage that could compromise safety or functionality.
- All exposed areas of both welds on the container were examined using Non-Destructive Examination (NDE) Liquid Penetrant (LP). The inspection procedure used was ASTM E165; however, no rejection criterion was set. The inspector was to report any noticeable defect or indication.

2.1.6 External Pressure Testing Method

The pressure testing was completed in three stages corresponding to the normal evolution load, maximum glacial loading, and up to container buckling. After each stage of testing, the container was then removed from the test vessel and inspected both visually and by liquid penetrant non-destructive examination.

The first stage of testing was a monotonic pressure increased to ~15MPa (test target of 2250psi or 15.5MPa); this pressure represents the conservative maximum normal load that would occur in the repository due to hydrostatic head and the buffer swelling pressure. This pressure was held for 10 minutes and then reduced back to ambient.

The second stage of testing was a monotonic pressure increased to ~45MPa (test target of 6650psi or 45.2MPa); this pressure represents the conservative maximum load that would occur in the repository due to the hydrostatic head of both the repository depth and 3000m thick glacier, as well as, the additive effect of the buffer swelling pressure. This pressure was held for 10 minutes and then reduced back to ambient.

The third and final stage of testing was conducted in two phases. The first phase was a monotonic pressure increased to ~45MPa (test target of 6650psi or 45.2MPa). This pressure was held for 10 minutes. This was followed by a slow monotonic rise to ~8000psi (55.2MPa), which was held for about 5 minutes. The re-check was performed at this pressure because the computational model results, completed prior to the testing, suggested that failure could occur as low as ~55MPa. This pressure milestone meant that buckling could occur at any time. The pressure was further increased at a slow rate (~25psi/minute) until failure.

2.2 Mechanical Integrity Model

2.2.1 Finite Element Model Setup: Materials, Geometry, and Boundary Conditions

The Mechanical Integrity Model (MIM) is a computational framework that was developed to evaluate the container under any postulated loading scenario. The MIM employs the Finite Element Method (FEM) using ANSYS Mechanical software. It capabilities include modelling of:

1. Large permanent deformation, including buckling collapse, through use of elasto-plastic material models with large-strain formulation and tolerant solvers (e.g. arc-length method)

2. Partial penetration weld zone and integral backing contact areas using augmented Lagrangian contact
3. Copper coating / bi-metallic composite response through use of the Cohesive Zone Model

In this application, we have used it to simulate the external pressure test of the steel-only container in the vertical orientation with the inner vessel inside. The inner vessel does not provide structural support or influence the buckling load; however, it has been included to simulate the ~1000kg gravity load localized on the hemi-spherical head contact area. The boundary conditions included vertical restraint at the bottom of the container to simulate contact with the lifting fixture's rubber pad, restraint of inner vessel about the central container axis (e.g. free floating in vertical direction only), and two planes of symmetry. The symmetric geometry and associated mesh are shown in Figure 6.

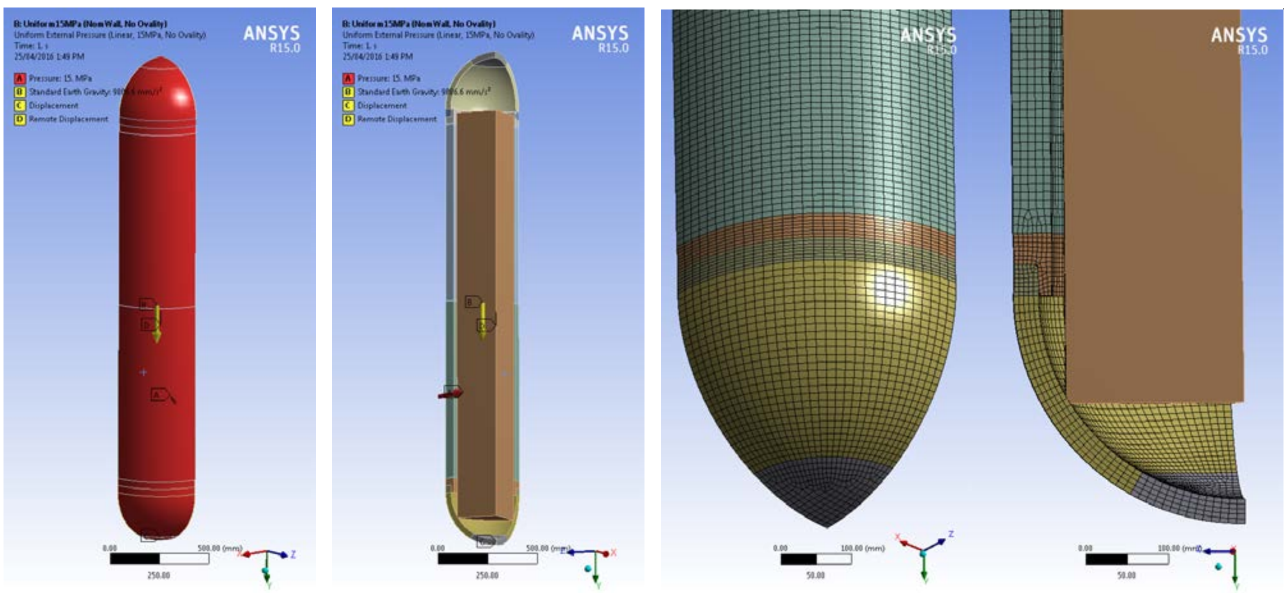

Figure 6 Mechanical Integrity Model of Mark 2 Used Fuel Container (1/4 symmetry) (a) Exterior view (b) Interior view with Inner Vessel (c) Mesh

The prototype container shell and heads are fabricated from A/SA-106 Gr.C and A/SA-516 Gr.70, respectively. In order to model large permanent deformation and buckling collapse, the plastic material behaviour beyond yielding, needs to be considered. Steel will generally strain harden beyond the yield point, requiring increasing load to continue the deformation. Depending on the yield strength and strain hardening rate assumption, the modelling results can vary widely. For completeness, we have run the model with four different material assumptions, summarized in Figure 7, to evaluate the effect on buckling load:

- ASME Perfectly plastic: This model assumes no strain hardening occurs; that is, the yield point and the ultimate tensile strength are assumed to be the same. This is known as perfectly plastic material and creates an additional safety margin compared to real world material behaviour. The yield strengths are taken from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section II minimum values.

- ASME Elasto-plastic: This model calculates a true stress-strain curve using the ASME BPVC Section VIII, Division 2, Annex 3.D methodology up to the ultimate true stress value. The yield and ultimate strengths are taken from the ASME BPVC Section II minimum values.

- Experimental tensile test data (lowest / highest yield strengths): This model uses the true stress-strain curves obtained from experimental tensile test data directly. Material properties can vary substantially between different heats (batches) of steel. We performed five tensile tests each for three different heats following ASTM E8. The experimental results with the lowest and highest yield strengths were evaluated.

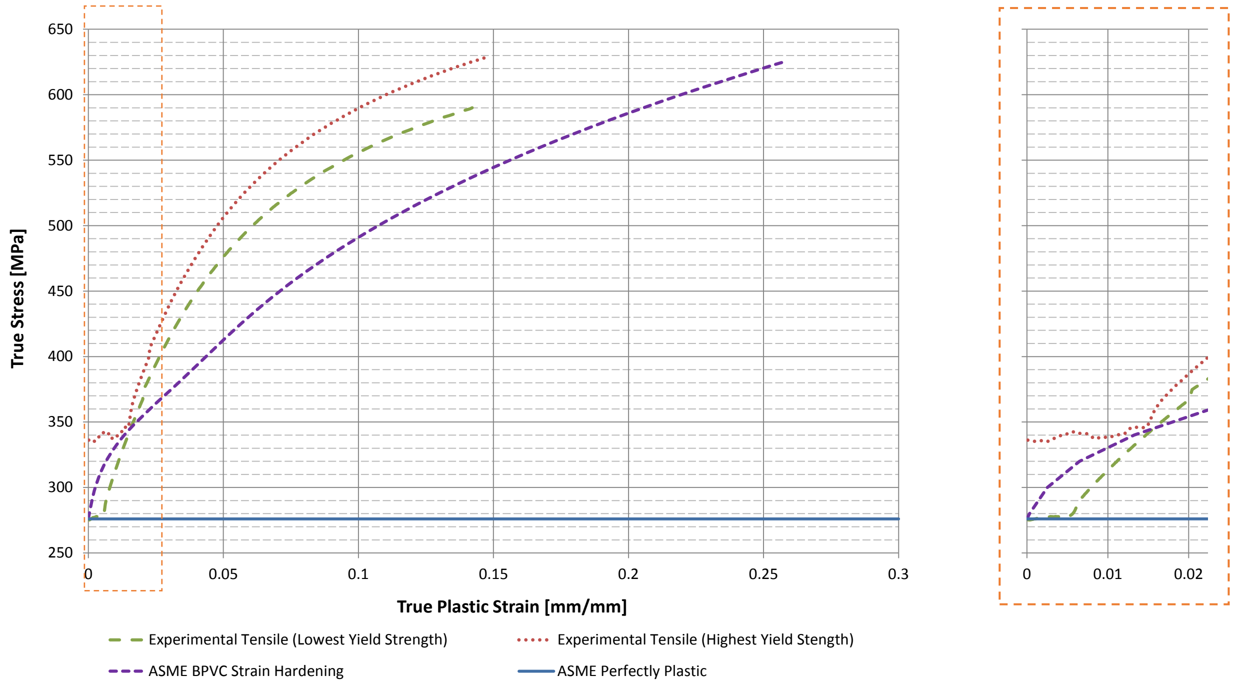

Figure 7 Tensile true stress-strain curves starting at the onset of yield

2.2.2 Modelling Buckling Collapse

Modelling buckling of thick walled structures cannot be accurately calculated using eigenvalue (Eulerian) buckling formulation. This approach assumes an ideal elastic structure leading to over prediction of the buckling load. A comprehensive modelling approach that mimics the imperfections found in real-world structures needs to be undertaken. To achieve this the MIM was augmented to include the following:

- Geometric deficiencies: Computer modelling allows us to create a perfectly cylindrical shell with flawless hemi-spherical heads. In reality, these components are machined steel and will have variations and flaws. The primary geometric deficiency that affects the buckling load is ovality of the cylindrical shell. A 1% ovality in the container shell has been shown to lower the buckling load by up to 12.4% compared to no ovality. In this model, we assumed an ovality equal to the OD machining tolerance limit representing the worst-case scenario.

- Large strain formulation: In linear elastic finite element analysis small-strain formulation is used. This method assumes the deflections (strains) from the applied load are so small that they do not change the geometry or material properties enough to influence the results significantly. This is typically a reasonable assumption for most steel structures designed to operate well below the yield point. Conversely, large strain formulation considers changes to geometry and material properties as the load is being applied. This is particularly important in this analysis because as the container deforms, it will become more oval, which further reduces the load carrying capacity.

- Non-linear material properties: The elasto-plastic material response is included in the model as discussed in 2.2.1 using isotropic hardening.

3. Results and Discussion

3.1 Experimental Test

3.1.1 Pressure Test Stage #1: Maximum Normal DGR Load (15 MPa)

The first stage of testing proceeded with no issues on the container. It was pressurized to ~2250psi (15.5MPa) and held for ten minutes. The strain gauges appeared to have several issues. 15 out of 24 failed or gave inconsistent readings during the initial test. Once removed from the pressure test vessel, the container, fixture, and all strain gauges visually appeared undamaged. No disbond had occurred on any of the potting. The resistances were checked on the strain gauges and all were still showing continuity. The post-test Liquid Penetrant NDE revealed no indications.

3.1.2 Pressure Test Stage #2: Maximum Glacial Load (45 MPa)

The second stage of testing proceeded with no issues on the container. It was pressurized to ~6650psi (45.2MPa) and held for ten minutes. Due to the results of stage 1, only 10 out of 24 strain gauges were recorded (an additional one in stage 1 that gave questionable results was included). All appeared to give reasonable readings. The resistances were checked on the strain gauges and all were still showing continuity. Once removed from the pressure test vessel, the container, fixture, and all strain gauges appeared undamaged. No disbond had occurred on any of the potting. The post-test Liquid Penetrant NDE revealed no indications.

3.1.3 Pressure Test Stage #3: Buckling Collapse (>45 MPa)

The third stage of testing proceeded by first re-pressurizing the container to ~6650psi (45.2MPa) and was further held for ten minutes. The pressure was then increased at a slow rate (~25psi or ~0.17MPa / minute) until failure occurred at 8302 psi (57.2MPa). Failure was noted by a rapid decrease in pressure of ~150psi (~1 MPa). For this test, we used all 24 strain gauges. The results from previous tests were often sporadic: blips in strain, non-monotonic increases / decreases, etc. As a result, it was decided that all would be recorded to see if they began operating properly as pressure increased. Once removed from the pressure test vessel the fixture and all strain gauges appeared undamaged. No disbond had occurred on any of the potting. The container had clearly buckled at the mid-shell, showing a distinctive oval shape along the shell. The post-test Liquid Penetrant NDE revealed no indications and the containment boundary was still intact.

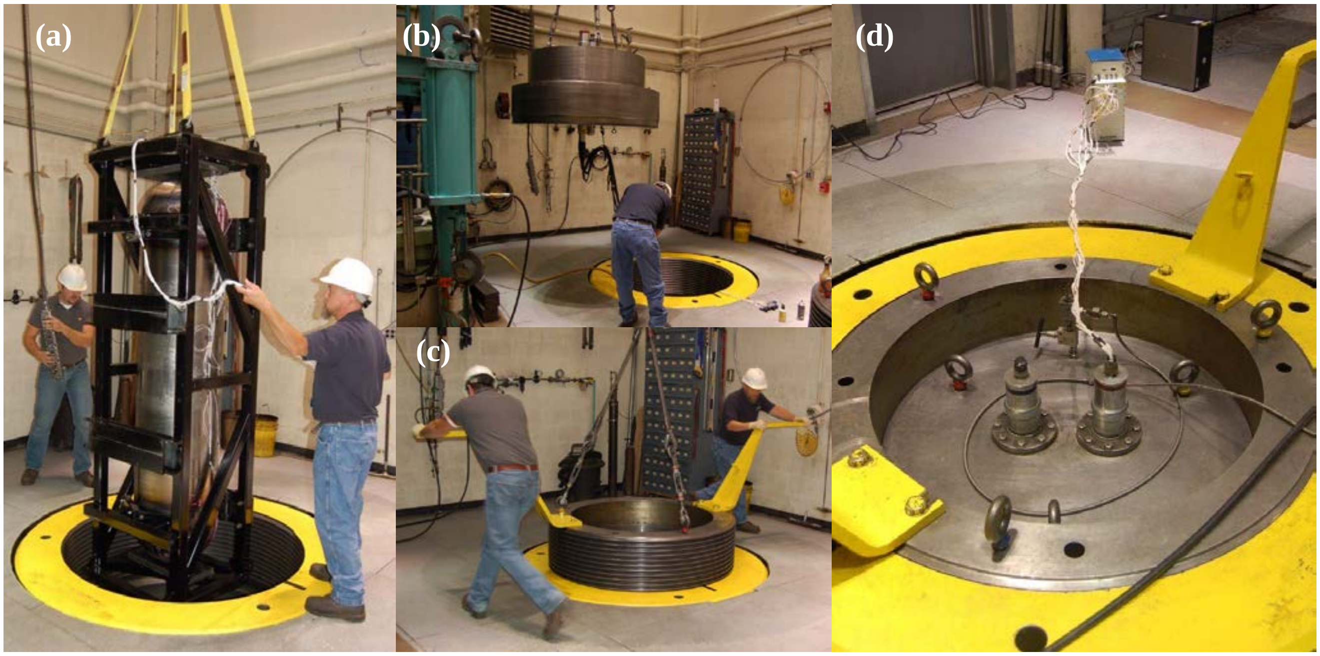

Figure 8   Mark 2 Used Fuel Container External Pressure Test (a) Loading container into pressure test vessel (b) Lid with internal strain gauge connections (c) Retaining ring installed (d) Strain gauge connections attached to digital acquisition system

3.2 Computer Model

The MIM predicted that the container would survive the 15MPa and 45MPa with limited localized plastic deformation at stress concentrations. All four models, corresponding to the various material assumptions, predicted buckling initiating at the mid-shell.

The deflection at the mid-shell of the container as a function of external pressure is shown in Figure 9. The deflection increases monotonically until reaching a peak value – the buckling load. At this point, the container's load carrying capability is exhausted and no additional pressure is required to induce a displacement change in the container geometry. The container rapidly deforms to a stable equilibrium configuration; in this case, the shell collapses against the inner vessel. The collapse is predicted to occur as low as 55.5MPa up to 65.6MPa depending on the material assumptions.

3.3 Comparison between Experiment and Computer Modelling

The experimental buckling load occurred at 8302psi (~57.24MPa) and was consistent with the computer modeling results as summarized in Table 1. The perfectly plastic material, as expected, produced the lowest buckling load followed closely by the lowest yield strength material. The lowest test result exhibited an upper yield strength followed by a ~276MPa yield plateau that is approximately perfectly plastic below 1% strain, hence the close result. The highest yield strength results in 14.6% higher estimate of collapse compared to the experimental result; nonetheless, the yield strength is almost 20% higher than the minimal material allowable. The ASME strain hardening model produced the closest results to the experiment.

It is important to note that we currently only have one pressure test data point on a prototype steel-only version of the container. Several more tests are planned to increase the data set including testing of a copper coated prototype in 2016.

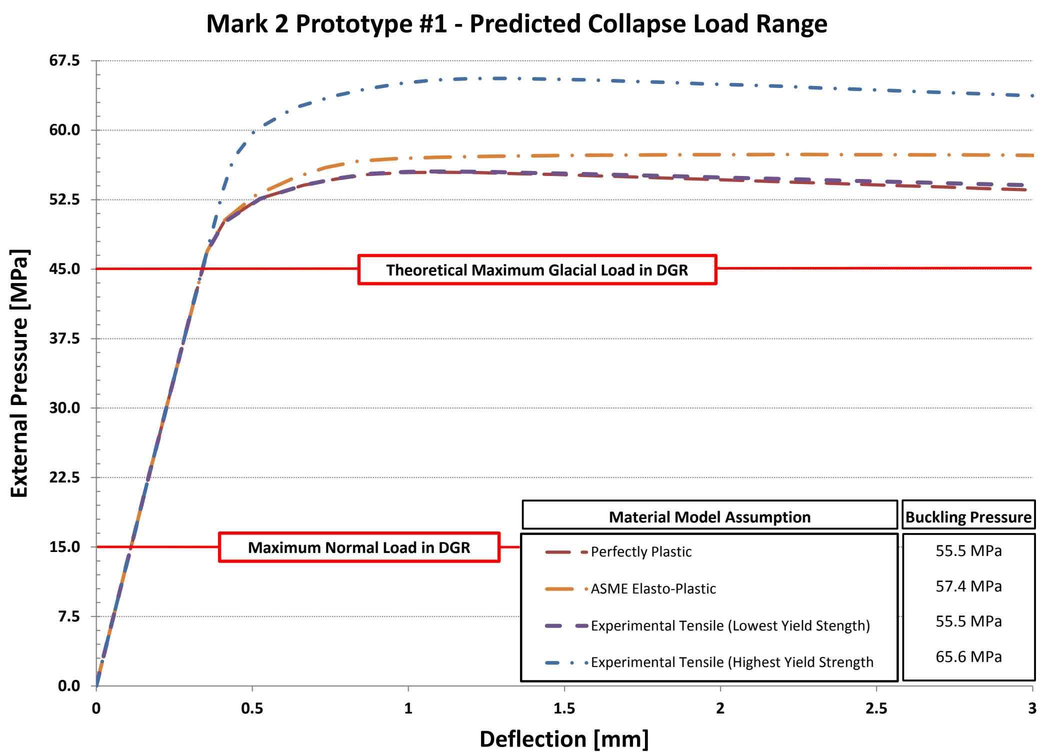

Figure 9 Computer modeling predicted deflection of Mark 2 container at mid-shell as a function of uniform external pressure. Peak value represents the onset of buckling (collapse).

Table 1 Mark 2 Used Fuel Container Buckling Loads Summary: Experiment and Computer Modelling

	Yield Strength [MPa]	Buckling Load [MPa]	Percentage Change from Experimental Results [%]
Experimental Pressure Test Results	N/A	57.24	N/A
Modeling: ASME Perfectly Plastic	276.0	55.47	–3.1
Modeling: ASME Strain Hardening	276.0	57.37	+0.2
Modeling: Tensile Data (Lowest Yield)	275.5	55.55	–3.0
Modeling: Tensile Data (Highest Yield)	327.6	65.60	+14.6

Strain gauge performance was inconsistent throughout all tests. Many gauges appeared to fail outright or give nonsensical readings. As a result, the planned comparison between the strain gauge outputs and the computer modeling results was not completed. Improvements to the strain gauge installation methodology have been proposed in collaboration with Penn State, as well as, the strain gauge manufacturer. These modifications will be implemented in the next test scheduled for late 2016.s

4. Conclusions and Future work

The experimental testing confirmed that the Mark 2 container can withstand the normal evolution and glacial loads without any detrimental effect to structural integrity; simultaneously validating the computational model and the manufacturing techniques. The visual inspections revealed no damage and LP NDE did not find any cracks or indications in the weld zone. The container was then loaded to the buckling load, which was achieved at 8302psi (~57.24MPa), consistent with the computational MIM modeling predictions. Several more external pressure tests are planned to augment the data set including pressure testing of a copper coated container in 2016.

5. References

[1] NWMO, 2005. "Choosing a way forward: the future management of Canada's used nuclear fuel", Nuclear Waste Management Organization, Toronto, Canada.

[2] SKB, 2011. "Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project - Volume I, II, II", SKB Technical Report TR-11-01. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

[3] POSIVA, 2013. "Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto - Models and Data for the Repository System 2012", Posiva Report 2013-01. Posiva Oy, Olkiluoto, Finland.

[4] ANDRA, 2014. "Everything you need to know about radioactive waste management", ANDRA Reference 337JVA. ANDRA, Châtenay-Malabry, France.

[5] NAGRA, 2013. "Annual Report 2013". National Cooperative for the Disposal of Radioactive Waste (NAGRA), Wettingen, Switzerland.

[6] J F Harrington, D J Birchall, 2007. "Sensitivity of total stress to changes in externally applied water pressure in KBS-3 buffer bentonite", SKB Technical Report TR-06-38.

[7] Boyle, C.H. and Meguid, S.A., 2015. Mechanical performance of integrally bonded copper coatings for the long term disposal of used nuclear fuel. *Nuclear Engineering and Design*, *293*, pp.403-412.