Structural Performance Assessment of Nuclear Fuel Waste Containers

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ABSTRACT

A summary of the structural performances of four conceptual container designs developed for the Canadian Nuclear Fuel Waste Management Program for the disposal of used nuclear fuel is provided. The performance assessments are based on comparisons between the predictions of analytical models and the results of hydrostatic tests conducted on prototypes of the designs. Although the comparisons range from extremely good to poor, the overall qualitative agreements are encouraging. It appears that some of the analytical models could be refined further to predict the test results more closely.

INTRODUCTION

In the Canadian Nuclear Fuel Waste Management Program (CNFWMP), a number of container designs are being developed for the disposal of used CANDU™* fuel in an underground vault constructed in plutonic rock (Figure 1). The container must be able to remain intact within the vault environment for a minimum of 500 years. In a 1000-m deep vault resaturated with groundwater, the container would be subjected to an external hydrostatic pressure of ~ 10 MPa at ~ 100°C. The CNFWMP includes materials evaluation and structural performance studies and the development of container fabrication and inspection techniques. This paper reviews studies conducted to determine the short-term structural performance of the following four candidate container designs: (1) Stressed-Shell, (2) Structurally-Supported, (3) Metal-Matrix and (4) Packed-Particulate. Each is capable of isolating up to 1.4 Mg uranium contained in 72 used CANDU™ fuel bundles. The structural performance of each design was assessed through a detailed stress/strain analysis, which was then compared to the results obtained from a hydrostatic test conducted on one or more prototypes.

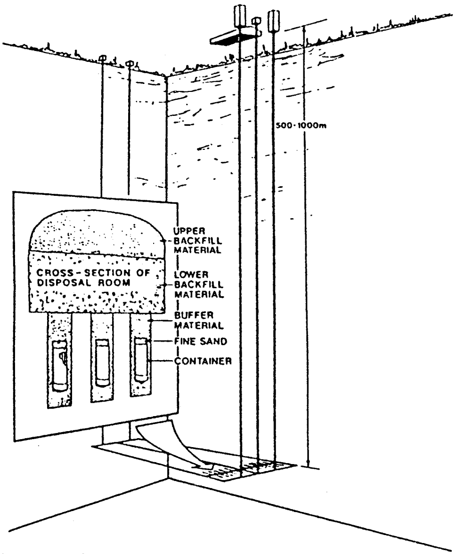

Figure 1: Schematic of Canadian Used-Fuel Disposal Vault Concept

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* Canada's natural-uranium, heavy-water reactor, Canada Deuterium Uranium

STRESSED-SHELL CONTAINER

In the Stressed-Shell design, the container shell is constructed with sufficient thickness to withstand the hydrostatic pressure and to provide adequate corrosion allowance for the required 500 years. A full-scale prototype, shown in Figure 2, was fabricated from 316L stainless steel and subjected to increasing hydrostatic pressure at 20°C until shell collapse occurred (Crosthwaite et al., 1982). Shell deformation was monitored by strain gauges installed at strategic locations on the structure. The test results were compared to the predictions of an axisymmetric finite-difference model developed using BOSOR5, a commercially available computer program.

The predicted and experimentally determined collapse pressures (19.51 MPa and 18.96 MPa, respectively) were in excellent agreement. The analysis predicted that stresses in the shell would reach the elastic limit first at a location near the crown of the top head, at a hydrostatic pressure of ~ 4.9 MPa. Up to 10 MPa, the predicted and measured circumferential strains at the mid-shell location agreed to within 4%. However, the meridional strains differed by up to 75%. As pressure was raised further, the experimental strain data diverged from the predicted strains, primarily because the shell became increasingly non-axisymmetric.

At regions containing discontinuities, the agreement between the predicted and experimental results was consistently poorer than at the mid-shell region. Strain data obtained from a three-gauge rosette installed on the upper head-to-shell weld are shown in Figure 3. At ~ 10 MPa, the experimental strains are about 70% higher than those predicted. Additional discussion is presented by Crosthwaite et al. (1982).

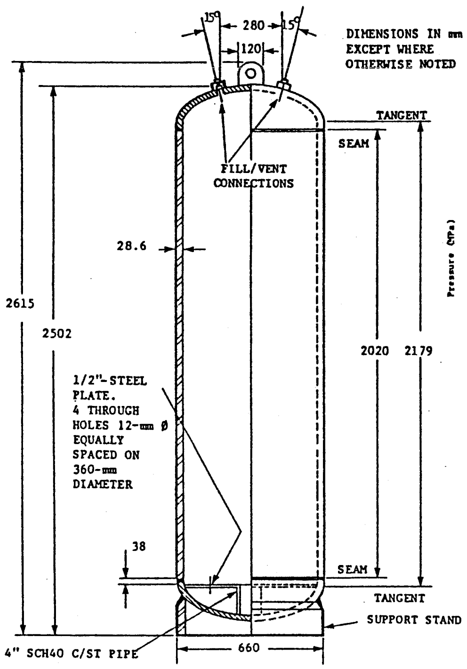

Figure 2: Stressed-Shell Container Test Prototype

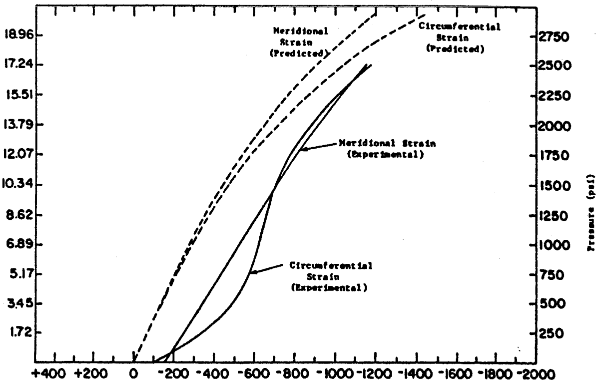

Figure 3: Results from Strain Gauges at Upper Head-to-Shell Weld (Stressed-Shell Container)

STRUCTURALLY SUPPORTED CONTAINER

In this design, support for the outer shell is provided by an internal fuel basket to which load is transferred by a granular material (glass beads 0.7-1.0 mm diameter). Following loading of the used fuel bundles into the basket, the tubes are sealed with press-fit plugs. The glass beads are then vibratory compacted between the shell and the basket, see Figure 4. A full-scale prototype was fabricated from ASTM Grade-2 titanium and subjected to an external hydrostatic pressure of 10 MPa at 150°C in a Hydrostatic Test Facility located at the Whiteshell Nuclear Research Establishment. The 150°C test temperature was selected on the basis of preliminary vault-temperature specifications. In later studies, the reference vault temperature was reduced to 100°C. Strain gauges were installed at strategic locations on the shell to monitor its deformation during pressurization. Further details are presented elsewhere (Hosaluk, 1985). Finite-element analyses were carried out by developing a radial cross-section model and an axisymmetric full-length model of the container, using the commercially available computer code ANSYS.

The test results showed that no shell buckling occurred and that the stresses remained below the elastic limit of titanium (200 MPa). Because the carbon-steel basket has a higher thermal expansion coefficient than the titanium shell, an outward radial force is exerted on the shell as the temperature is increased. The test results (Hosaluk, 1985) reflect this effect: shell deformations under external pressure were lower at 150°C than at 20°C. The predictions of circumferential stresses in the shell from the two-dimensional radial model and the corresponding test results are shown in Figure 5. At all positions on the shell, the analytical model correctly indicates that all stresses would remain below the elastic limit; however, it overestimated the stress levels. At point A, the particulate layer appears to offer considerably more support to the shell than at points B and C. The predictions of stress for the ends of the container using the full-length model were significantly higher (>75%) than those obtained from the test results. These discrepancies appear to be due to inaccuracies in the modeling of the properties of the particulate material and to the limitations of a two-dimensional analysis.

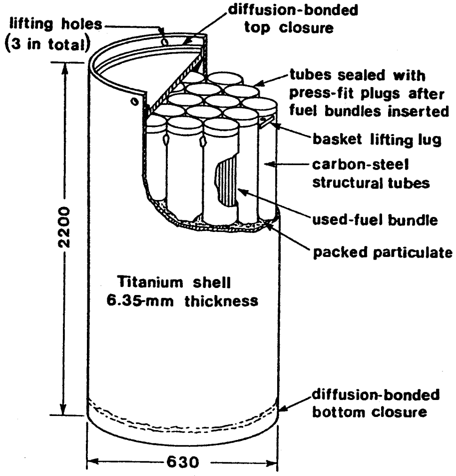

Figure 4: Structurally Supported Container

METAL-MATRIX CONTAINER

Figure 6 shows the Metal-Matrix design in which the support for the shell is provided by a cast matrix of a low-melting-point metal such as lead. Because the weight of a full-scale lead-matrix prototype could not be accommodated in the Hydrostatic Test Facility, the test program was conducted on half-scale models. Four models were tested, of which three were fabricated with various deliberate casting voids in the matrix (Hosaluk et. al., in preparation).

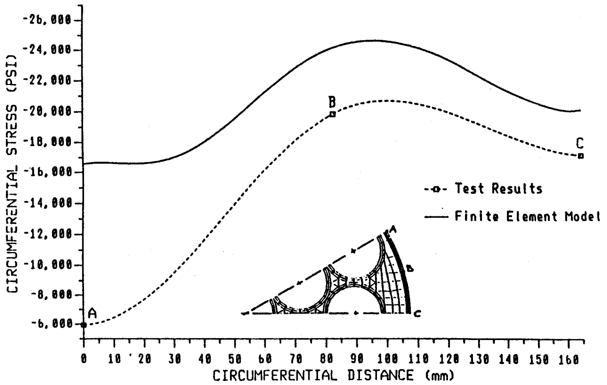

Figure 5: Radial Model Results for the Structurally Supported Container

One model included a large void between the top of the matrix and the top head, see Figure 7. An axisymmetric finite-element computer model of this container was developed from the commercially available computer program MARC and is described in detail by Grover (1988).

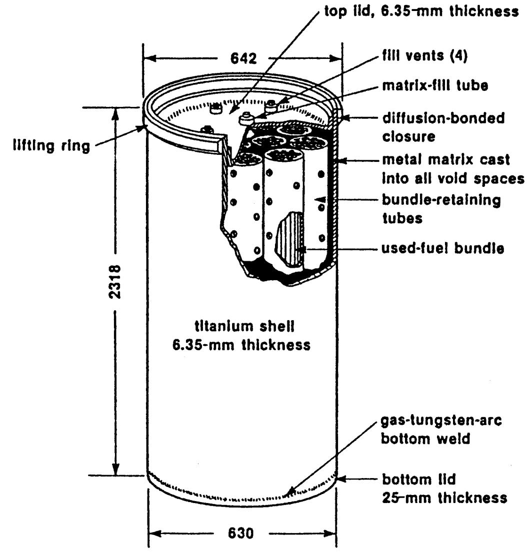

Figure 6: Titanium-Shell Metal-Matrix Fuel Isolation Container

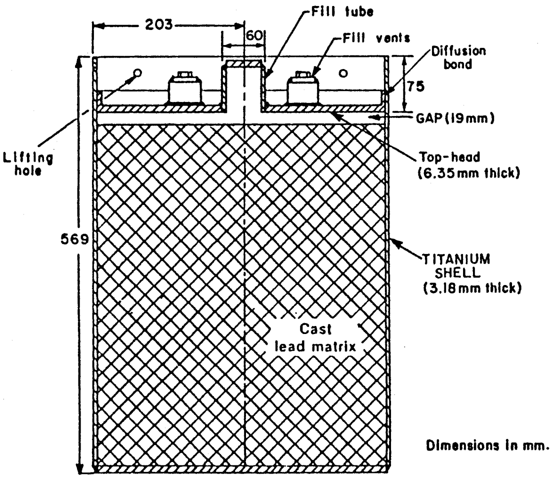

Figure 7: Half-Scale Metal-Matrix Test Prototype

The analytical results indicated that the first onset of plasticity in the shell occurred at 0.33 MPa external pressure. As pressure was further increased, the top head deflected downward until it contacted the matrix at 2.1 MPa. At 10 MPa, the maximum stress (339 MPa) occurred at the junction of the top head and the shell. The qualitative agreement between the analytical predictions and test results was encouraging. However, the post-test examination of the container revealed the presence of a large circumferential bulge along most of the length of the shell between the top and bottom heads. Figure 8 shows the post-test shell profile at a location 88 mm below the top head. Figure 9 shows the effect of this bulge on the strain gauge data. The cause of this large deformation response is not known. It may be either a unique buckling response of the shell or result from a fabrication defect or local material weakness. However, metallographic examination of samples of the shell from this region revealed no unusual material structure. Because the analytical model includes axisymmetric constraints, it was unable to predict this discontinuity.

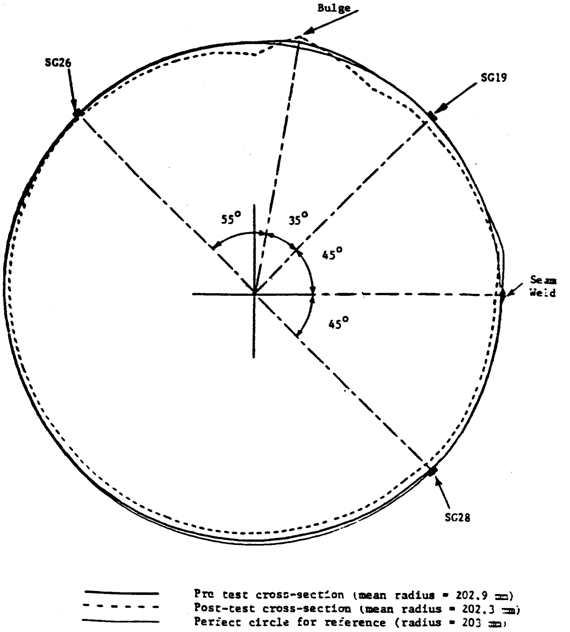

Figure 8: Cross Section of Metal-Matrix Test Prototype (88 mm from the top-head)

PACKED-PARTICULATE CONTAINER

In the Packed-Particulate container design, internal support for the shell is provided solely by compacted glass beads. The carbon-steel tubes of the fuel basket (see Figure 10) are thinner than those of the Structurally Supported design and are not sealed. All voids, including those between the fuel elements of the bundles, are filled with compacted beads. A full-scale titanium-shell prototype was fabricated and tested to a maximum hydrostatic pressure of 10 MPa at 150°C. Again, strain gauges were installed on the shell to monitor deformation. Further details are presented by Teper (1988). Four finite-element models of various regions of the container were developed. The analyses were based on linear-elastic properties of the container materials and were carried out using the commercially available computer program ABAQUS (Teper, 1988).

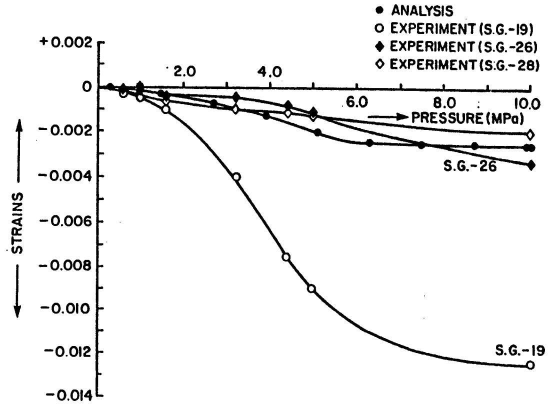

Figure 9: Circumferential Strains at Strain Gauge Positions Shown in Figure 8

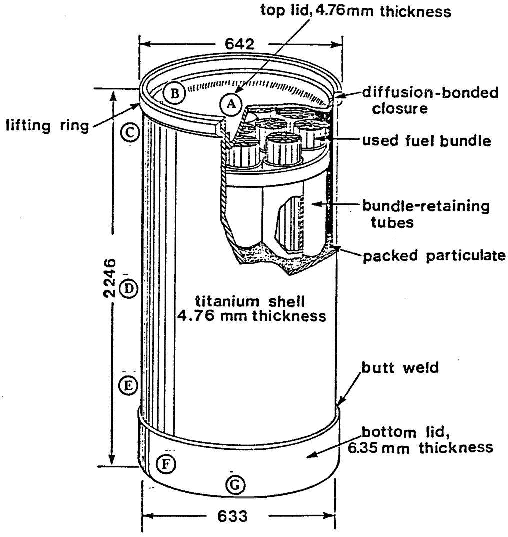

Figure 10: Packed-Particulate Fuel Isolation Container

The test results showed that stresses in the shell remained below the elastic limit, whereas the top head experienced plastic deformation (Teper, 1988). The predicted and experimental shell strains are compared in Table 1. Except for the circumferential strain at location D (mid-shell), poor agreement was obtained. The main factors contributing to these discrepancies were the use of simplified analytical models and uncertain mechanical properties of the particulate material. The analysis was further refined by including non-linear gap effects, which resulted in some improvement in the predicted results.

Table 1

Strains from the Test and Analysis (Packed-Particulate Container)

Location (1)	Strains (μm/m)			
	Test Results (2)		Analytical Results	
	Axial	Hoop	Axial	Hoop
A	200	-220	1400	1300
B	-950	60	1011	-400
C	-1460	-2210	-997	-1636
D	-30	-1500	-650	-1814
E	40	-115	-84	-1702
F	(3)	(3)	-70	-860
G	(3)	(3)	-45	-45

Notes:

1. See Figure 10 for locations.
2. Test results were obtained at 10 MPa and 125°C.
3. Not monitored during the test.

After consideration of the short-term structural performance of all candidate thin-shell container options and other factors such as ease of fabrication and inspection, handling, cost, etc., the Packed Particulate design was selected as the reference option for the Concept Assessment Phase of the CNFWMP.

CONCLUSIONS

The short-term structural tests have clearly demonstrated that all container designs can successfully withstand the hydrostatic pressure expected in the vault. No breach of the container boundary occurred and the stresses in regions away from structural discontinuities were generally below the elastic limit of the material. Analytical models developed to date for the prediction of the short-term structural behaviour of candidate container designs for the disposal of Canada's used fuel have been partially verified by structural performance tests conducted on prototypes of the designs. The major limitations of the models appear to be related to the use of axisymmetric constraint and the need for a more accurate understanding of the mechanical behaviour of compacted particulate material. Axisymmetric models cannot accurately account for a variety of structural and material non-linearities nor post-buckling behaviour of the shell. Further, they cannot identify non-symmetric buckling modes that could occur at lower pressures. Work is now underway to develop more refined structural performance models that include three-dimensional analyses.

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