RECENT DEVELOPMENTS IN DESIGN OF CONTAINERS FOR DISPOSAL OF HIGH LEVEL WASTE FROM CANDU REACTORS

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ABSTRACT

The Research Division of Ontario Hydro is currently developing two container concepts for the disposal of used fuel from CANDU nuclear reactors. The Thin-Walled, Particulate-Packed container uses a thin titanium shell as an isolation barrier and for corrosion protection. A granular material such as packed glass beads provides the structural support. The Iron-Based, Stressed-Shell container also has a thin titanium shell for corrosion protection. This shell is overpacked on a thick steel cask which provides the structural support.

CONTAINER DESCRIPTION

As part of the Canadian Nuclear Fuel Waste Management Program, Ontario Hydro Research Division is developing two containers for the long term isolation of used fuel bundles removed from CANDU nuclear reactors. Thin-Walled, Particulate-Packed.

The Thin-Walled, Particulate-Packed

(TWPP) container has a thin (4.76-mm thick shell with a 6.35 mm bottom plate) outer shell made of B265 grade 2 titanium (see Fig. 1)/1,2/. The basket containing irradiated fuel bundles is made of nineteen 4-inch (100 mm), 0.125-in (3.175 mm) wall steel tubes. Each basket can contain up to seventy-two 495-mm long bundles. It is supported from the bottom by an open grid. The outer shell is structurally supported by a granular material (particulate) such as glass beads packed into the voids inside the basket and between the basket and the titanium shell./1/

The TWPP container has been selected as the design for the reference engineering study for the Concept Assessment Phase of the Canadian Nuclear Fuel Waste Management Program.

Iron-Based, Stressed-Shell

The Iron-Based, Stressed-Shell (IBSS) container, in Fig. 2, has a thick steel cask for structural support. It is overpacked with 4.35-mm thick titanium shell for corrosion protection. The cylindrical shell of the cask is made of 24-inch (610 mm), Schedule 80 pipe. Top and bottom heads are made of flat plates 76-mm thick. The bottom head is full penetration welded to the steel shell. The top head

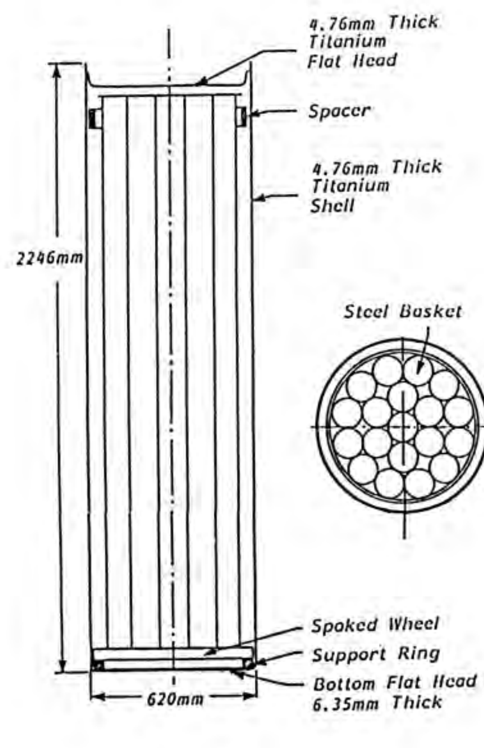


Fig. 1. TWPP Container.

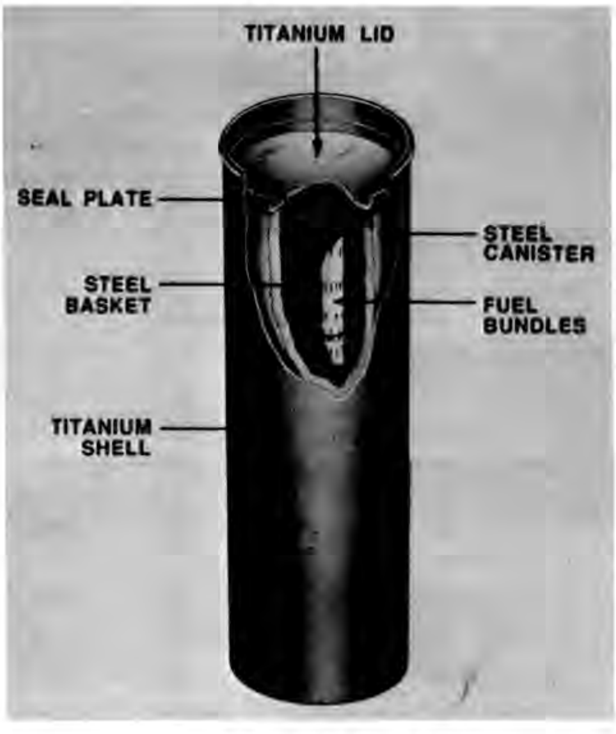


Fig. 2. IBSS Container.

(installed in the hot cell) will be press fitted and seal welded /3,4/.

In the basket used with this container, the spoked wheel and support ring are replaced by a 12.7 mm steel plate. The container has been analyzed and shown to be structurally durable by a finite element analysis.

LOADING CONDITIONS

The containers are designed to satisfy several structural performance conditions. Penetration due to corrosion must not occur for 500 years. The containers must be able to support an external pressure of 10 MPa that might occur in a 1000-m deep disposal vault saturated with ground water. Outer shell temperature may reach 100°C. The container must be able to support an internal pressure of 0.06 MPa due to the increase in internal temperature.

DESIGN CRITERIA

There are no standards providing design criteria applicable to disposal containers. The steel cask of the IBSS container is a pressure boundary and it is qualified using the ASME Boiler and Pressure Vessel Code,Section III, Subsection NE (for MC components). The titanium shell does not support any external loads and it is considered to fail only if large strains cause it to tear. A preliminary study indicated that theshell will not tear if the sum of two local tensile strains is below 5.3% /4/. Compressive stresses in the shell are not considered to cause failure, unless buckling occurs.

The Code does not require creep analysis for low temperature applications. However, because of the 500-year required container life, the creep buckling of a container using manufacturing tolerances that produce the worst stress configuration must be considered.

TWPP CONTAINER PROGRAM

The mechanical properties of particulates including Young's modulus (Ep), Poisson's ratio (l) and bulk modulus (B) were determined from uniaxial compression tests, with the granular material confined in a thick-walled cylinder closed by thick pistons/5/ (see Table I).

TABLE I

Properties of Particulates

NO.	PARTICU-LATE	μ	Ep (GPa)	B (GPa)
1	Wedron Sand	0.32	457	423
2	Glass Beads	0.41	337	624
3	Interprop	0.30	336	281
4	Bauxite	0.34	285	297
5	Rutile	0.33	238	233

The measured heat transfer coefficients of the particulates were low. Heat generated by the bundles will be primarily transferred out of the container axially through the basket tubes. Other properties of the particulates tested in this program included dust content and the ability of the particulate to flow well in the space restricted by bundles.

Preparation of the Prototype

A prototype of the TWPP container shell was built from formed and welded titanium plates/6/. The basket was filled with simulated fuel bundles and placed inside the container. The container was filled with glass beads. The particulate was compacted on a shaker table using sinusoidal vibrations of 4g peak-to-peak at 50 Hz frequency for 10 minutes. The container was instrumented with 48 bondable double and triple rosette gauges and with 6 single weldable gauges. Seven additional weldable gauges were installed for monitoring the last two stages of the test (tests with voids in particulate)/6/. A special multilayer sealing procedure was developed for installing the bondable gauges for underwater elevated pressure and temperature application/7/.

The container was transported to the test facility at the Whiteshell Nuclear Research Establishment in Manitoba, Canada. During this 800 mile trip, the particulate settled further forming an up to 14.5 mm high gap at the top. The test program consisted of 7 stages:

- preliminary test at 20°C and 1 MPa
- initial test at 100°C and 10 MPa
- second test at 125°C and 10 MPa
- a test at 150°C and 10 MPa
- 16-day test at 150°C and 10 MPa
- center void test at 150°C and 10 MPa
- side void test at 150°C and 10 MPa

The two voids were artificially introduced by drilling holes in the shell, vacuuming out particulate and welding a plug to seal the holes.

Results of the test program were compared with those of the numerical (finite element) analyses to demonstrate the adequacy of the numerical method and to give confidence in results of analyses beyond the scope of the test program/8/.

Computational Methods

The finite element analyses were conducted using the ABAQUS computer code. Most of the models were axisymmetric to reduce the execution time of the non-linear problems. Two-noded, axisymmetric shell elements and four-noded bilinear axisymmetric solid elements were used.

To show that an axisymmetric assumption was valid, a horizontal, cross section of the container was analyzed with the basket tubes modeled explicitly. The variation in the calculated radial displacement was less than 5%. The axisymmetric assumption was *considered* valid. In the model, measured mechanical properties of particulate were used (see Table I). The calculated deformations in the cylindrical titanium shell were similar to those measured in prototype tests providing better confidence in results of subsequent analyses.

Preliminary Test

During the first, preliminary test at 1 MPa, large strains were measured in the top head. Measurements following the last stage of the test/9/ showed that the top head settled down by up to 14.5 mm - the height of the gap during the test (see Fig. 3).

The closing of the gap during the preliminary test was confirmed in the finite element analysis. Deformations in the head were calculated as a function of pressure (see Fig. 4). It shows that most of the plastic deformation occurred below 1 MPa.

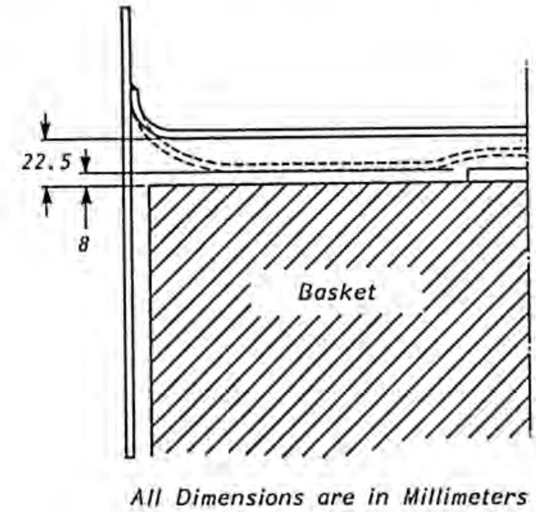


Fig. 3. Void Under Top Lid.

Tests at 10 MPa

In the first 10 MPa, 100#C test, some plastic deformations occurred, largely in the rim of the top lid. This was confirmed in the analysis (see Figs. 4 and 5). In subsequent, higher temperature tests all strains were elastic only, including the 16-day test/6/.

Comparison of strains in the cylindrical shell, for the first 10 MPa test, was good (see Fig. 5). In the rim of the top lid, strains varied widely and comparison became more difficult (see Fig. 6).

Most of the bondable gauges performed well during the 100#C test, but failed by the time the 150°C (stage 4) test was completed. Results from only a limited number of weldable gauges were obtained.

Tests With Voids

In the last two stages of the hydrostatic tests, two voids were artificially created. The first void was located below the center of the top lid where 0.21 l of particulate were removed. For the subsequent test, 0.8 l of particulate were removed from an area in the corner between the top head and the cylindrical shell. Tests with voids resulted in large localized plastic deformations. Figure 7 shows the plastic deformation in the center of the top lid following the test with the center void. The void spread over most of the top lid area. Strains in the cylindrical shell were unaffected by the void. The void was simulated analytically. Although the calculated plastic strains differed at low pressures, as the pressures were increased above 5 MPa the results were very similar (see Fig. 8). The initial variation is attributed to the

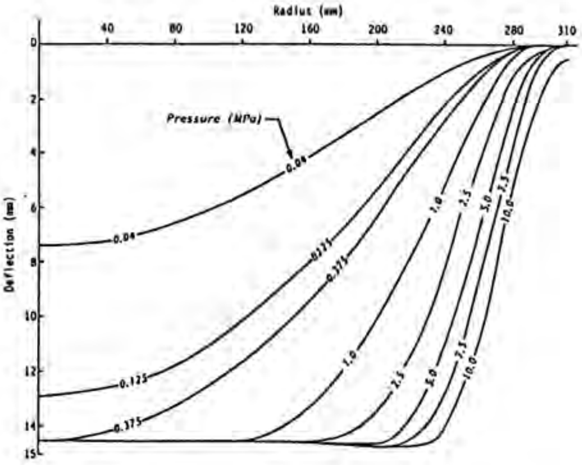


Fig. 4. Closing of Top Void.

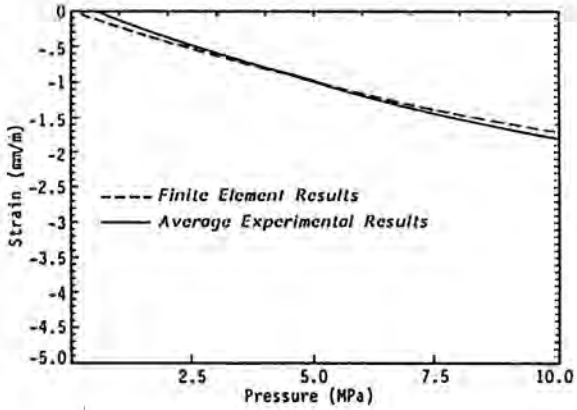


Fig. 5. Plastic Deformation in Shell.

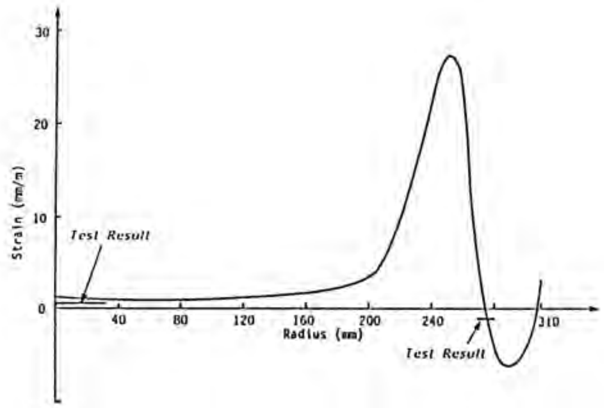


Fig. 6. Strain in Rim of Top Plate.

Fig. 7. Deformation in Top Head at Position of Center Void.

effects of drilling and plugging the hole used to extract particulate.

A test of the container with a side void produced significant deformation in the top lid and in the cylindrical shell adjacent to the void (see Fig. 9). The double "buckling" wave was caused by the basket spacer ring. Strains measured in the cylindrical shell were large and non-linear at the side void. But 90° away from the void (in hoop direction), strains were unaffected by the void (see Fig. 10).

A similar deformation in the top head and in the shell (including the double "buckling wave) was obtained using a finite element model, as shown in Fig. 11. A comparison of

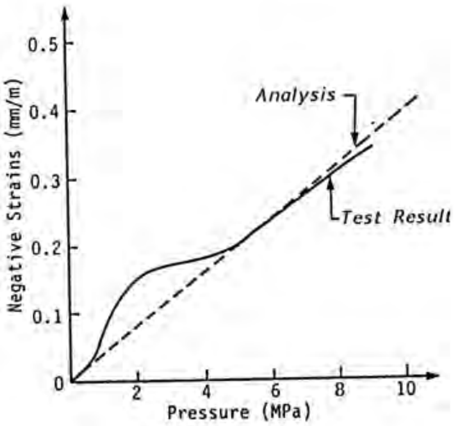


Fig. 8. Strains at Center Void.

plastic strains was more difficult here and successful plots of strains were not obtained.

Extension of Analysis

The finite element analyses were extended beyond the scope of the tests based on the good correlation between the test results and analyses/8/.

The container will be lifted at the top rim of the container. The weight of the container contents (19,200 N) will then be supported by the bottom plate producing stresses in the titanium shell below 25 MPa.

A fully assembled container will be placed in an up to 1000-m deep underground vault in a prepared borehole. The borehole will be closed by compacting a mixture of sand and bentonite clay above the container. An analysis was conducted which showed that equivalent static pressure used for the compaction must be limited to 9.5 MPa.

a) In Top Head

b) In Shell

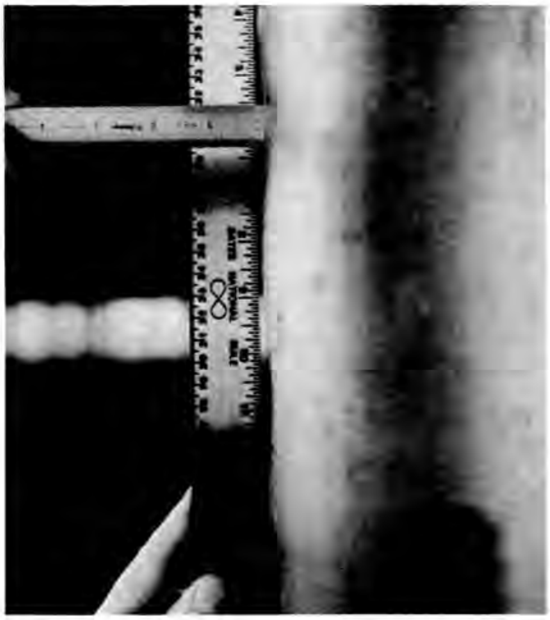
An increase in the internal container temperature by 90°C would increase the internal pressure by about 0.04 MPa. The particulate head would produce an additional internal pressure on the shell of 0.02 MPa resulting in tensile stress of 110 MPa (about 60% yield) at the head to shell discontinuity.

If the 1000-m deep disposal vault is saturated with groundwater, the external pressure on the container will be 10 MPa, as used in the analysis discussed above. Non-uniform swelling of the backfill (sand and bentonite mixture) can exert an additional local pressure of up to 3 MPa. Preliminary analyses indicate that this pressure would not increase local strains significantly.

IBSS CONTAINER PROGRAM

The Iron-Based, Stressed-Shell container was qualified

a) In Top Head



b) In Shell

Fig. 9. Deformations at Side Void.

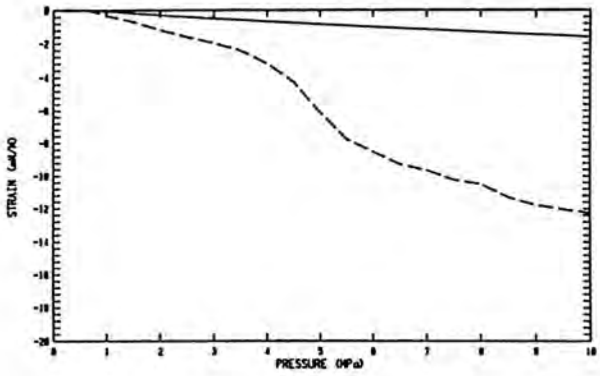


Fig. 10. Strains From Rim Void Test.

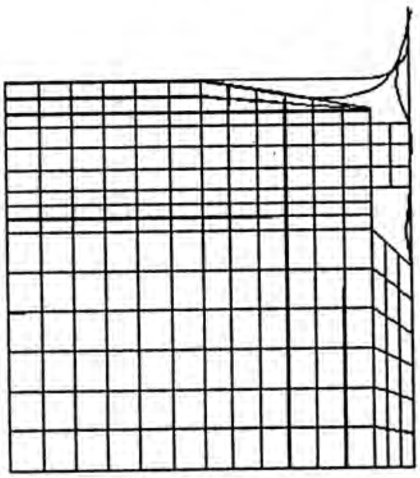


Fig. 11. Calculated Deformations.

in an extensive analytical program. The qualification was based on the structural performance of the steel cask. Creep induced buckling limited the external pressure the cask can support. The titanium shell was assumed to deform the same amount as the steel cask plus 1-mm to account for clearance.

Creep in Steel

Studies were carried out to determine the creep properties of steel at low temperature. Properties available in the literature/7/ were extrapolated for a cask temperature of below 125°C; high stress, approaching yield (at cask temperature) and for the 500-year postulated container life. Results of the extrapolation are shown in Fig. 12. To verify the results of this triple extrapolation, a test program was carried out. Results of the 2,000 to 4,000 hr. tests were extrapolated using exponential creep assumption to 500 years and plotted in Fig. 12/5/.

The test program indicated that at stresses below 67% yield, creep is not anticipated. For stress between 67 and 80% yield, a logarithmic creep law is applicable. As the stress approaches yield, an exponential law must be used and large creep strains may occur. Results of the tests, illustrating these observations are shown in Fig. 13.

Stresses in the Cask

Finite element method was used to evaluate the stress distribution in the steel cask, using axisymmetric solid elements. Stresses in the cask were shown to be within the Code allowables. Stresses in the cylinder and in the heads, away from the cylinder-to-head junctions, were below 50% yield. Creep is not expected in these areas. In the junctions, average stress is still below 67% yield, but linear-elastic local

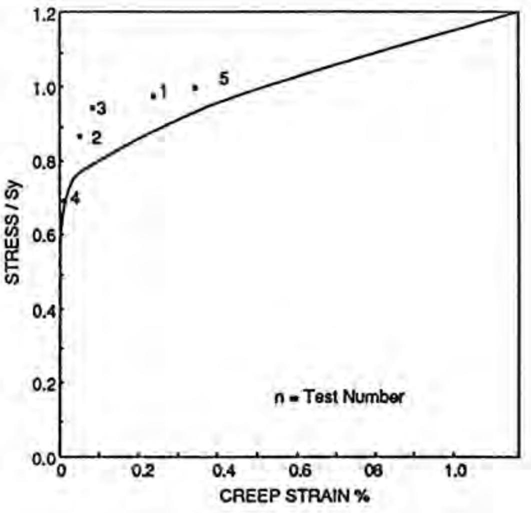


Fig. 12. Estimated 500 Year Creep.

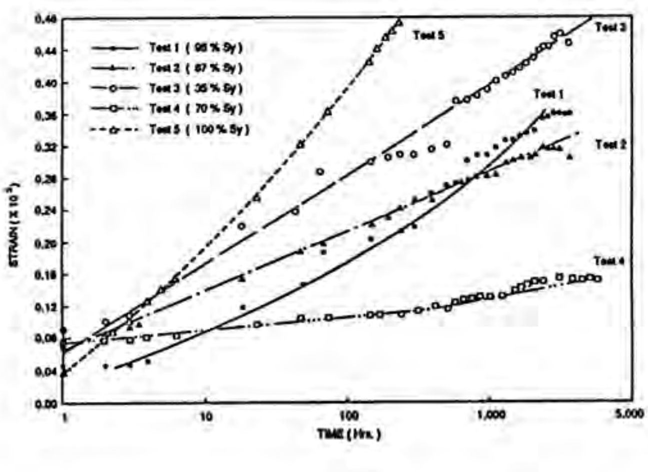


Fig. 13. Creep Test Results.

peak stress exceeds 110% yield. High bending and peak stresses can result in creep induced deformations.

Buckling Analysis

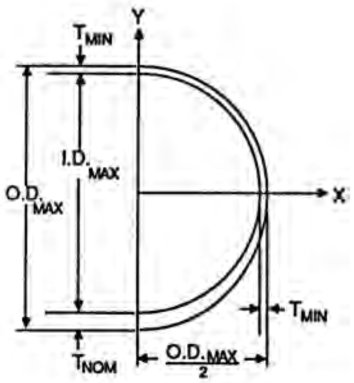
A three dimensional model of the cask was created using shell elements to evaluate the pressure at which the cask buckles. The largest out of roundness and thickness variation allowed by the ASTM Standard A 530 (see Fig. 14) were assumed. The stress strain curve for ASTM 1020 steel was linearized for the stability analysis. The analysis predicted a buckling pressure of 16.8 MPa, using the buckling criteria of ASME Code (NE-3228 and Appendix II-1430(B)). The Code allowable buckling pressure is 11.2 MPa. The buckled shape of the container is shown in Fig. 15.

Creep Induced Buckling

An analytical study was carried out to determine if a time dependent buckling analysis can be simplified by modifying the stress-strain curve used in the analysis to include anticipated 500-year creep. Both time dependent and modified curve analyses predicted identical results. The modified stress-strain curve is shown in Fig. 16. The finite element model for the buckling analysis was used here again. Reaction moments showing the containers' ability to resist buckling (see Fig. 17) indicate that buckling may initiate at about 11 MPa external pressure, after 500-year creep Fig. 16 Stress-Strain Curve with Creep

Closure System

A final closure was considered using a 76-mm thick full penetration weld. Such a weld would be difficult to achieve and inspect. Instead, we propose a thick steel disc press fit into the end of the steel shell. The outer edge of the disc and the inner surface of the shell will have a slight (6°) taper to produce a secure, self-locking closure/8/. Based on the results of 1/4 scale models, the closure is expected to support an internal pressure of up to 8 MPa. The interference fit used limits the leak rate through the closure. Leak rates



Dimensions for 24" Schedule 80 Pipe

T_{MIN} = 27.08 mm
$T_{NOMINAL}$ = 31.04 mm
$O.D._{MAX}$ = 612.78 mm
$O.D._{MIN}$ = 608.81 mm
$I.D._{MAX}$ = 554.66 mm

Fig. 14. Geometry for Buckling Model.

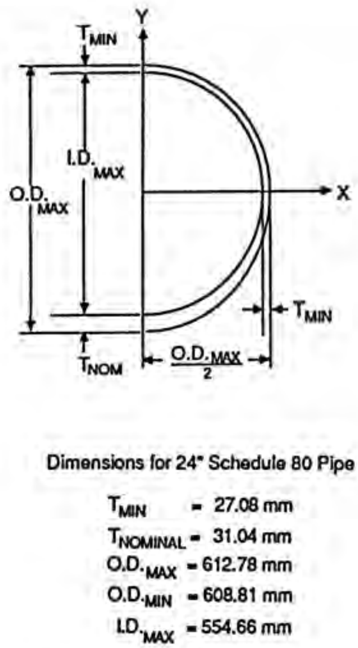


Fig. 15. Post-Buckling Shape.

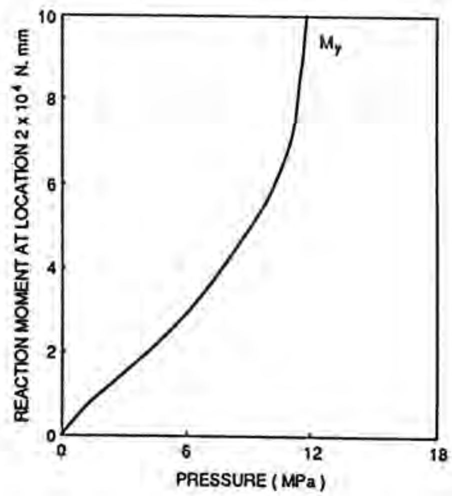


Fig. 17. Bending Moment in Cask Shell.

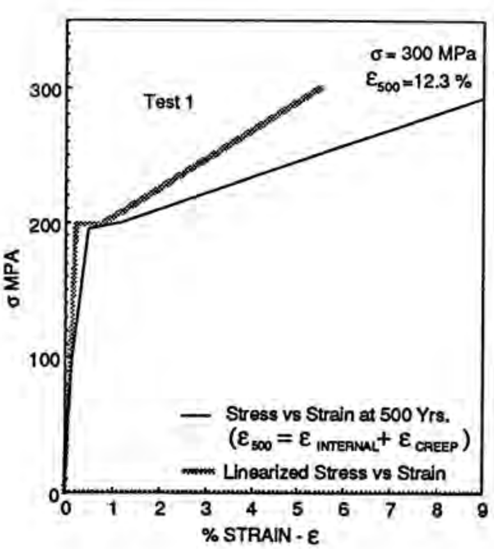


Fig. 16. Stress-Strain Curve With Creep.

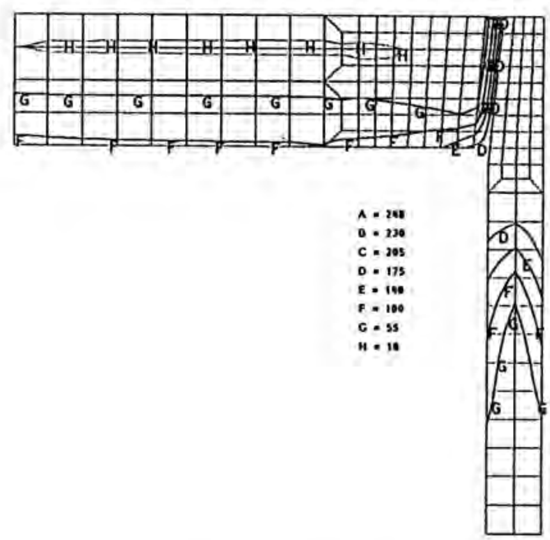


Fig. 18. Stresses in Closure Area 0 MPa Pressure.

obtained in the scaled test program ranged from below 10^{-9} to 10^{-3} atm cc/sec. A seal weld is required to ensure a leak tight closure.

Stresses in the closure area were calculated using the finite element method. The 6° taper was included in the model. An interference fit of 0.7 mm was imposed on the closure using gap elements. As the external pressure was increased from 0 to 10 MPa, the behaviour of the closure was monitored. Stresses in the closure area did not change significantly due to the external pressure - the pressure induced stresses are small in comparison with the interference stresses (see Fig. 18 and 19). As the pressure increased, an unwelded closure opened at the top by 0.002

mm. Seal welding is required to prevent the closure from opening.

Titanium Shell

The titanium shell is made by forming, fitting and welding thin titanium plates over the steel cask. The manufacturing process will be controlled to ensure that radial clearance between the shell and the cask is less than 1 mm. In the corner between the cylindrical shell and the top plate, the titanium shell will be unsupported. Two analyses were conducted. One included a reinforcing ring in the corner (see Fig. 20). In the second analysis the ring was removed.

Finite element analyses of the 4.76-mm titanium shell indicated low plastic strains throughout. The largest plastic strains were calculated in the corners of the top and bottom heads at 0.3% and 0.12%, in the cylindrical shell. Strains were similar with and without the reinforcing ring.

Overpressure Consideration

D.A. Dixon and M.N. Gray/10/ postulated that the vault backfill material around a container may swell when saturated with water. The additional swelling pressure may reach 3 MPa.

To accommodate this additional pressure, the cylindrical shell of the steel cask should be increased to 41.3 mm. The outside diameter of the shell would increase to 622 mm. This could be achieved by rolling a non-standard pipe or by centrifugal casting.

CONCLUSIONS

Two programs are being conducted in parallel on two different container designs. Based on tests and analyses conducted to-date, both containers provide a viable alternative for disposal of used fuel bundles from Candu nuclear reactors.

Both programs are continuing.

REFERENCES

1. B. Teper, "Feasibility Assessment of the Thin-Walled, Particulate- Packed Container, Proceedings of Waste Management '86 conference in Tucson, Arizona, March 2-6, 1986.
2. R. Hoy, M. Mikasinovic, "Particulate-Packed, Thin-Wall Container - Prototype Design", Ontario Hydro, Design and Development Division Report, June 9, 1981.
3. B. Teper, "Evaluation of Iron- Based, Stressed-Shell Container", proceedings of Waste Management '86 conference in Tucson, Arizona, March 2-6, 1986.
4. B. Teper, S.A. Reid, "Assessment of the Iron-Based, Stressed-Shell Container", Ontario Hydro Research Division Report 89-12-K.
5. B. Teper, "Test Program of Granular Materials for the Thin-Walled, Particulate-Packed Container", Ontario Hydro Research Division Report 87-154-K, Dated August 27, 1987.
6. B. Teper, "Test Program of the Prototype of the TWPP Container, Part 1 - Hydrostatic Tests", Ontario Hydro Research Division Report 84-316-K, December 29, 1984.

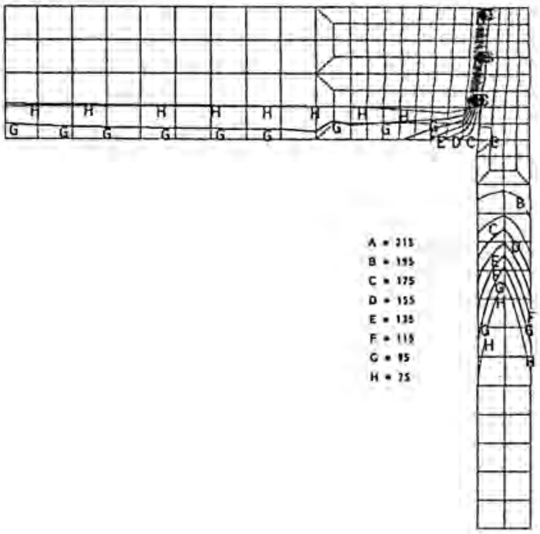


Fig. 19. Stresses in Closure Area 10 MPa Pressure.

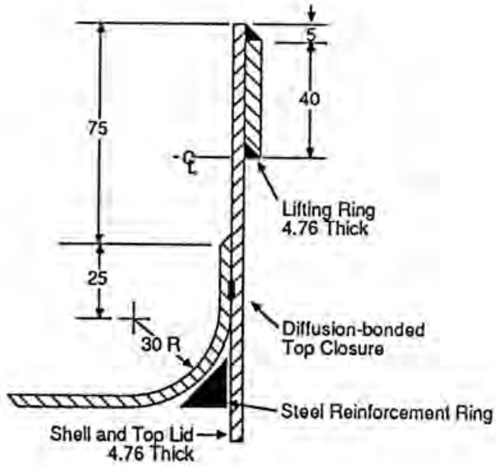


Fig. 20. Design of Top Lid Corner.

7. J. Russell, "Protection of Bondable Strain Gauges Under Severe Conditions (10 MPa Water 150#C Using Sealed Cap Method", Ontario Hydro Research Division Report 83-481-K, December 23, 1983.
8. B. Teper, "Test Program of the Prototype of the TWPP Container, Part 3 - Detailed Stress Analysis", Ontario Hydro Research Division Report 87-296-K, July 15, 1988.
9. B. Teper, "Test Program of the Prototype of the TWPP Container, Part 2 - Post Hydrostatic Tests", Ontario

Hydro Research Division Report, 85-313-K, November 20, 1985.

10. D.A. Dixon, M.N. Gray, P. Baumgartner, G.L. Rigby "Pressures Acting on Waste Containers in Bentonite-Based Materials", 2nd International Conference on Radioactive Waste Materials, September, 7-11, 1986, Winnipeg, Manitoba, Canada.