# FEASIBILITY ASSESSMENT OF THE THIN-WALLED, PARTICULATE-PACKED CONTAINER

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## ABSTRACT

The Thin-Walled, Particulate-Packed container is being developed for the disposal of used fuel bundles from CANDU Nuclear Power Generating Stations. The concept has been shown to present a viable option for such disposal. This was demonstrated in an extensive set of tests conducted on a full-scale prototype and by analysis. The prototype was found to have adequate strength to support an external pressure of at least 10 Mpa at temperatures up to 150°C. The container was assembled without significant difficulty. Deformations measured following the hydrostatic test suggest that the particulate was packed without detectable voids. The particulate's strength and creep resistance were found to be acceptable.

## INTRODUCTION

The responsibility for developing disposal methods for used fuel from CANDU Nuclear Generating stations lies with the Atomic Energy of Canada Limited (AECL). Under a mutual agreement [1], Ontario Hydro is involved in a Technical Assistance Program (TAP) to AECL. The development program for the Thin-Walled, Particulate-Packed (TWPP) container is conducted as a part of this agreement. The TWPP container concept is one of several disposal container designs currently being considered.

The TWPP container is being developed for isolation of unreprocessed used fuel bundles in an up-to 1000 m deep vault [2]. A conceptual vault diagram is illustrated in Fig. 1.

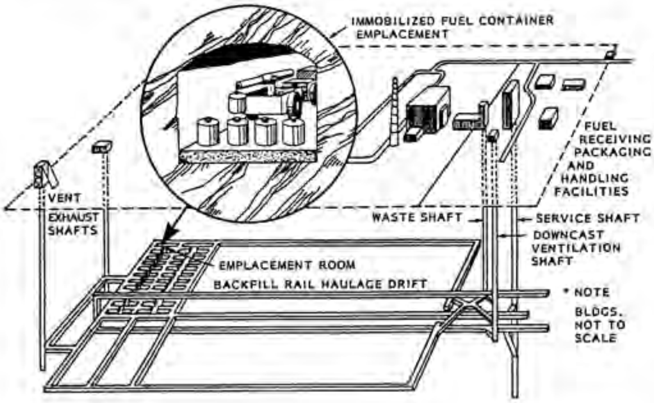


Fig. 1. Layout of Repository.

In this concept, the bundles are placed in a thin steel basket which is then placed in a thin titanium shell and all void space in the container filled with a granular material (particulate). A cross-section of the assembled container is shown in Fig. 2.

The project was divided into several phases: evaluation of selected particulates; container design; design and construction of the prototype container; prototype tests and feasibility assessment.

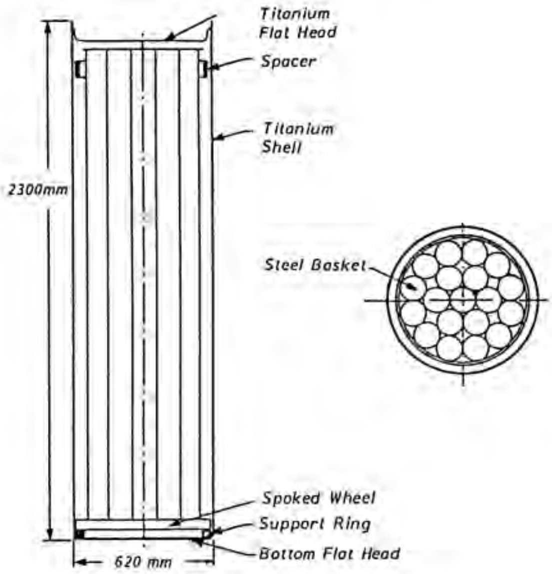


Fig. 2. Layout of TWPP Container.

## CONTAINER DESIGN

### Design Criteria

The container was designed to support the following loading conditions:

- An external hydrostatic pressure of 10 Mpa (1470 psi)
- An internal pressure due to the increase in the internal temperature by 130°C, assuming no external pressure.
- Total container weight during lifting.
- Dynamic loads due to vibratory compaction.

There are no codes or standards directly applicable to disposal containers that would provide the guidelines for stress limits. The ASME Boiler and Pressure Vessel Code, Section III was used where possible. In cases where this code could not be used, a factor of safety of two on ultimate strength was used.

### Design Description

The TWPP container consists of a low-carbon steel basket assembly with a capacity of 72 fuel bundles resting inside a cylindrical titanium shell. The empty space inside the container is filled with a granular material compacted by vibration to form a structural matrix. The container is 2185 mm high and has an inside diameter of 620 mm.

The outer shell is made of rolled B 265 grade 2 titanium plate, 4.76 mm thick. The top lid is 4.76 mm thick and would be resistance bonded to the shell after assembly (in a hot cell). The bottom plate has a larger thickness of 6 mm to support the weight of the particulate and the basket during lifting.

The basket consists of nineteen, 4-in Schedule 10 tubes concentrically arranged, as shown in Fig. 2.

Lifting attachments are provided at the top of the cylindrical shell, above the top lid. In this arrangement, there are no lifting loads on the top plate.

## EVALUATION OF PARTICULATE

Container integrity largely depends on the mechanical properties of the particulate, its long term stability and the effect of chemical interactions between the particulate and the shell and bundle materials (titanium and zirconium). We needed a material that would flow freely into confined space, but that when packed, would provide strong and stable structural support. Several types of particulates were tested including: glass beads, Wedron sand, steel shot 0.6-1.0 mm and bauxite grains (up to 1 mm). Other types of particulate are still being considered. These preliminary tests have shown good fluidity and strength of all tested particulates.

The selection of particulate for the prototype test program was based on two tests: a vibratory compaction test, in which particulate packing characteristics were determined and an axial compression test to determine strength, modulus of elasticity, Poisson's ratio and bulk modulus.

Glass beads were used to pack the prototype container because they have low dust content, adequate strength, good packing characteristics and good mechanical stability. As well, the chemical composition of glass can be tailored to ensure that there are no adverse reactions with other materials in the container.

### Packing of Particulate

Test equipment consisting of a long plexiglass tube attached to a shaker table and containing two dummy fuel bundles was used to test the packing characteristics of sample particulates. A small, plexiglass tube was inserted in the centre of the bundles and, while the system was stationary, particulate was poured into the tube to a level 10 mm above the bundles. The *bundles* did not offer significant resistance to the flow of the particulate. To further improve the packing density, sine wave vibration was applied at several frequencies and accelerations for five minute periods. No voids could be found after the packing process.

Release of dust was observed during pouring of some of the particulates into the tube. Sand produced a noticeable amount of dust, while the coarse glass was relatively dust free. The fine glass beads formed a small amount of dust.

The weight and volume of particulate were monitored before and after each part of a test. The densities are compared in Table I with a "reference density" equal to the density of a matrix having a face-centre-cubic configuration of uniform and equal size spheres. The reference density is equal to about 74% of a solid block of the particulate material.

TABLE I

Vibratory Compaction Test Results

| TYPE OF PARTICULATE | REFERENCE DENSITY $\rho r$ (kg/L) | ($\rho/\rho r$) MAX (%) | DENSITY OF POURING $\rho$(kg/L) | FREQ (Hz) | DENSITY $\rho$(kg/L) |
|---|---|---|---|---|---|
| SAND | 1.932 | 84.7 | 1.58 | 80 | 1.637 |
| SAND-BUNDLES NOT INCLUDED | 1.932 | 87.0 | 1.55 | | |
| SAND | 1.932 | 89.1 | 1.56 | 60 | 1.715 |
| SAND | 1.932 | 89.0 | 1.55 | 70 | 1.72 |
| FINE GLASS (0.002-0.3mm DIA) | 1.780 | 97.8 | 1.60 | 90 | 1.73 |
| GLASS BEADS (0.8-1.2mm DIA) | 2.221 | 91.4 | 1.97 | 45 | 2.03 |

Good packing was obtained during pouring. The "as poured" packing had a density of 80% to 90% of the reference density. A large variation in the grain size of the fine glass resulted in better packing density. However, some stratification of various sizes was also observed. Higher accelerations improved packing.

An increase in the frequency from 25 to 90 Hz significantly improved packing. The improvement was small as frequency was increased further to 180 Hz.

### Strength of Particulate

The following properties of particulate were determined, using the procedures described in reference 3:

- strength to break-down
- Poisson's ratio
- bulk modulus
- shear modulus of elasticity
- equivalent Young's modulus of elasticity

Fig. 3. Equipment for Particulate Compression Test.

The strength of various particulates was tested using the test apparatus *shown in* Fig. 3. The cylinder was open at both ends and supported on a flexible rubber pad. The particulate was compressed between two pistons. This double compression improved the uniformity of the axial component of the stress in the particulate[4]. A typical pressure distribution in the dual compression cylinder is shown in Figure 4.

The particulate properties are listed in Table II for 10 MPa pressure. This table also lists the mechanical properties of solid blocks of material similar in composition to the tested particulates. Steel shot was the strongest particulate tested. Glass beads and bauxite are weakest. The ratios of the moduli of a particulate over that of titanium are shown in Table II, column Ep/Et. The Young's moduli of the particulates vary with external pressure as shown in Fig. 5.

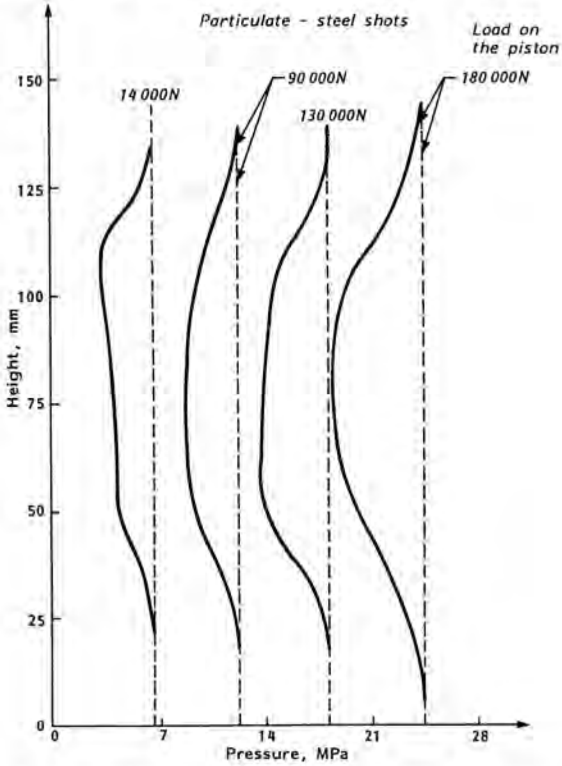


Fig. 4. Pressure Distribution in Dual Compression Cylinder.

TABLE II

Strengh of Particulates

| Particulate or Solid Material | Test Pressure MPa | Poison Ratio V | $E_p$ MPa | $\beta$ MPa | $E_p/E_t$(1) |
|---|---|---|---|---|---|
| *PARTICULATES* | | | | | |
| *Wedron Sand* | *12.0* | *0.32* | *457* | *423* | *0.0046* |
| *Glass Beads 0.6-0.9* | *12.0* | *0.40* | *283* | *472* | *0.0028* |
| *Glass Beads 1.0-1.2* | *12.0* | *0.35* | *297* | *330* | *0.0030* |
| *Glass Beads 1.4-1.68* | *12.0* | *0.35* | *303* | *337* | *0.0030* |
| *Prototype Particulate* | -- | *0.41* | *336* | *772* | *0.0034* |
| *PARTICULATE WITH BUNDLE* | | | | | |
| *Wedron Sand* | *9.7* | *0.26* | *1,662* | *1,151* | *0.0166* |
| *Glass Beads 0.6-0.9* | *9.7* | *0.18* | *2,337* | *1,220* | *0.0234* |
| *Glass Beads 1.0-1.2* | *9.7* | *0.34* | *1,041* | *1,055* | *0.0104* |
| *SOLID MATERIALS* | | | | | |
| *Steel* | -- | *0.29* | *200,000* | *160,000* | *2.00* |
| *Titanium* | -- | *0.34* | *100,000* | *110,000* | *1.00* |
| *Glass(3)* | -- | *0.20* | *69,000* | *38,000* | *0.69* |
| *Quartzite* | -- | *0.14* | *82,700* | *38,300* | *0.83* |

*(1) $E_t$ = 100,000 MPa - Young's modulus of titanium*

*(2) The shown values are for illustration only as they vary widely with compostion and treatment.*

Compression tests were also conducted at elevated temperatures of 160° to 200° C. Properties of particulates do not change significantly between the ambient and elevated temperatures at pressures of up to 50 Mpa.

## Creep of Particulate

Particulate evaluated during the compaction tests was tested for long term mechanical stability (creep), at temperatures above 150°C and a pressure of 10 Mpa. The creep test equipment is shown in Fig. 6. Poor initial packing resulted in the significant settlement in the early stages of the test. The tests lasted 600 to 1200 hours. In addition to long term, steady state tests, the behaviour of particulates under pressure and temperature cycling was evaluated.

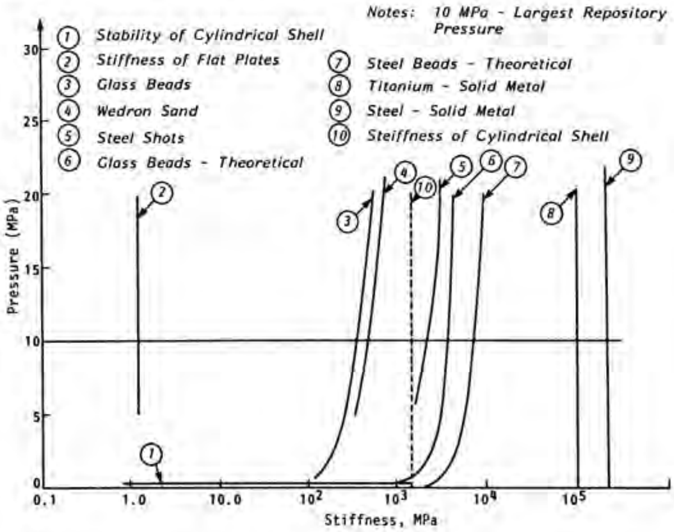


Fig. 5. Stiffness of Particulates.

Fig. 6. Creep Test Station.

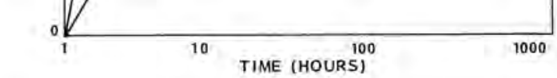


Fig. 7. Settlement of Particulate Under Constant Pressure and Temperature.

The settlement of particulate follows a logarithmic curve (see Fig. 7). Although reliability of extrapolating a 41-day test for an extended period of time is difficult, it indicates a settlement of less than 0.005% after 500 years, for glass or sand. Pressure or temperature cycling produced larger settlement than steady state loading. For example, a steady-state testing of glass for 1000 hr at 150°C produced a settlement equal to two pressurization cycles from 0 to 10 Mpa.

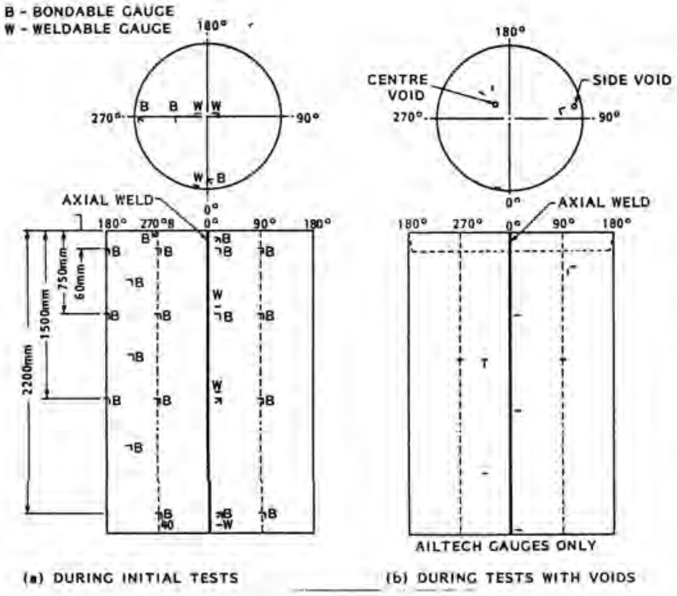
## BUILDING OF PROTOTYPE

A single, full-scale prototype was built as close to the dimensions of the original design as possible. The outer shell was made of titanium SB 265, grade 2. To provide the container with similar strength to that expected in an actual disposal container, 48 simulated fuel bundles were inserted in the outer ring of the basket. Glass beads 0.70 mm to 1.00 mm diameter were used as particulate[5].

## PROTOTYPE ASSEMBLY

A shaker table (see Fig. 8) was constructed such that the actuator was attached near the container's centre of gravity. In compaction we used sine wave excitation at accelerations of up to 4 g peak-to-peak in the horizontal direction only. Vertical excitations were not used because of the possibility of particulate to flow under the internal basket.

Fig. 8. Shaker Table.



(a) DURING INITIAL TESTS (b) DURING TESTS WITH VOIDS

Fig. 9. Location of Strain Gauges.

Initially, 635 kg (1400 lbs) of particulate were used to fill the container. An additional 68 kg was added as the particulate settled during shaking, to retain the level at 25 mm above the basket.

## CONTAINER INSTRUMENTATION

The prototype container was extensively instrumented with both bondable and weldable (Ailtech type) straingauges. Three thermocouples were used to monitor temperatures at different elevations. Because the strain gauges worked in harsh environment, the bondable strain-gauge instalation methods used involved multiple encapsulations. Several additional weldable, Ailtech type gauges were installed for two tests with induced voids. The locations of the gauges used during those tests are shown are Fig. 9.

## HYDROSTATIC TEST PROGRAM

Since only one prototype was planned, an extensive set of hydrostatic trials was designed, consisting of seven stages:

Preliminary tests - ambient temperature of 20°C, up to 1 MPa pressure
Stage 1 - initial test at 100°C and 10 MPa pressure
Stage 2 - second test at 125°C and 10 MPa
Stage 3 - full temperature test at 150°C and 10 Mpa
Stage 4 - 16-day, long term test at 150°C and 10 MPa
Stage 5 - centre void test at 150°C and 10 MPa
Stage 6 - side void test at 150°C and 10 MPa

The bondable gauges performed well during preliminary tests at temperatures of 100° and 125°C. During the 10 Mpa, 150°C test, all bondable gauges failed. Only data from the weldable gauges was used.

### Preliminary Tests

Instability of the cylindrical shell was anticipated at pressures below 0.25 MPa, if particulate was not used. Several low pressure cycles at 20° C were conducted. The top lid was the only area where noticable plastic deformation occurred (up to 0.05% strain) during the first low pressure cycle. All other strains measured during these cycles were small.

The lack of large displacements during these initial tests showed that the container was packed well with no significant voids.

### First-Stage Test

The first stage test was conducted with the prototype container heated to 100°C. A maximum pressure of 10 MPa was reached. The test was completed successfully. Plastic deformations observed in the preliminary tests, continued during pressurization to 10 MPa. A permanent strain of 0.005% was recorded at the rim of the top lid. Large deformations were observed in the top lid, although strains measured at the gauge locations were low. The top lid settled down from about 22mm above the basket to about 7 mm, as illustrated in Figure 10.

Strains were measured at four elevations. Just below the top lid, the average hoop strain was -0.33%. This is about twice the axial strain, which averaged -0.18%.

Away from discontinuities, the hoop strains were compressive at -0.2%. The hoop strain near the axial weld (discontinuity) is the highest at -0.23%. Only a small, positive axial strain was measured. We believe that this strain was due to Poisson effects. The axial force on the container is supported by the basket and particulate.

Total strains in the hoop direction near the bottom plate were compressive at less than 0.2%. The axial deformation is produced by Poisson effects.

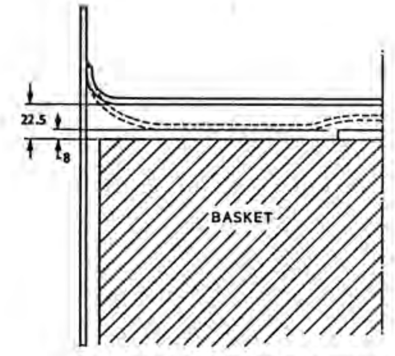


Fig. 10. Permanent Deformation of the Top Lid During First-Stage Test.

Second Stage Test

Readings were taken during pressurization at steps of 0.5 MPa. The last reading was taken at 9.5 MPa. Strain measurements during depressurization are not available as the test ended prematurely because of a seal failure in the test vessel. Strains measured during the pressurization were generally lower than strains obtained during the first stage test. Fig. 11 shows the comparison of strains on the cylindrical shell. Strains in the top lid away from the rim are low and do not change significantly between tests. This is due to the nearly parallel settlement of the top plate, as shown in Fig. 10.

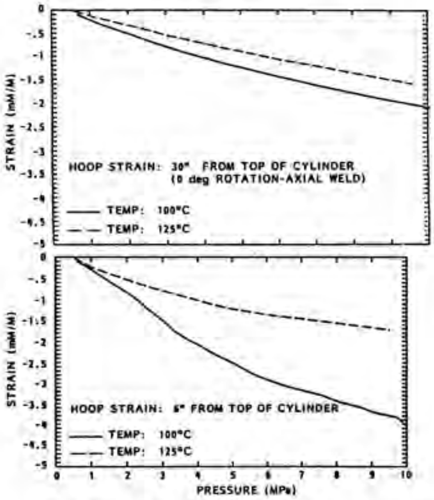


Fig. 11. Strains During 125$^{0}$C Test - Cylindrical Shell.

Third Stage Test

The third stage test was successfully conducted at 150° C. A full pressure of 10 MPa was applied. Good strain and temperature measurements were obtained during pressurization and depressurization. Plastic deformation was not seen during this stage.

Long-Term Test

The fourth pressure cycle was intended to show longer term stability of the container. The pressure and temperature were maintained for 16 days. An examination of the container following the test did not reveal any significant additional plastic deformation.

The strain variation due to the external pressure and time are shown in Fig. 12. In the cylindrical shell, the pressurization and depressurization curves are similar. The time dependent curve (Fig. 12b) is almost a straight, horizontal line.

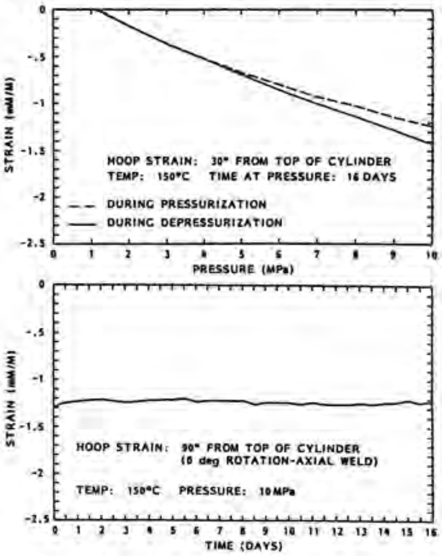
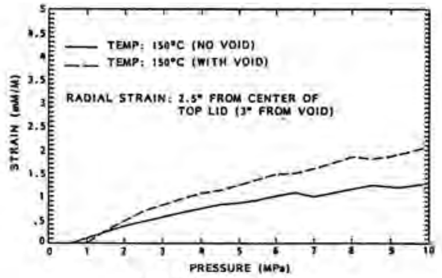
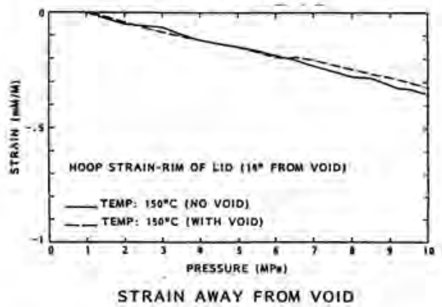


Fig. 12. Long Term Test Results Away from Discontinuity.

Fig. 13. Deformation of Top Lid Following Test with Center Void.



STRAIN AT VOID



STRAIN AWAY FROM VOID

Fig. 14. Strains Due to Center Void.

## Centre Void Test

A 0.21 L void was introduced under the center of the top lid to assesss the effect of imperfect packing. Void dimensions were about 15 mm depth and 125 mm diameter. During the 10 MPa, 150°C test, a localized dent of about 250 mm diameter and 6 mm depth formed in the top lid. The deformation around the void is shown in Fig. 13. Away from the void, the strain difference disappeared (see Fig. 14).

INSTABILITY OF CYLINDRICAL SHELL

DEFORMATION OF TOP PLATE

Fig. 15. Comparison of Strains with and Without Rim Void.

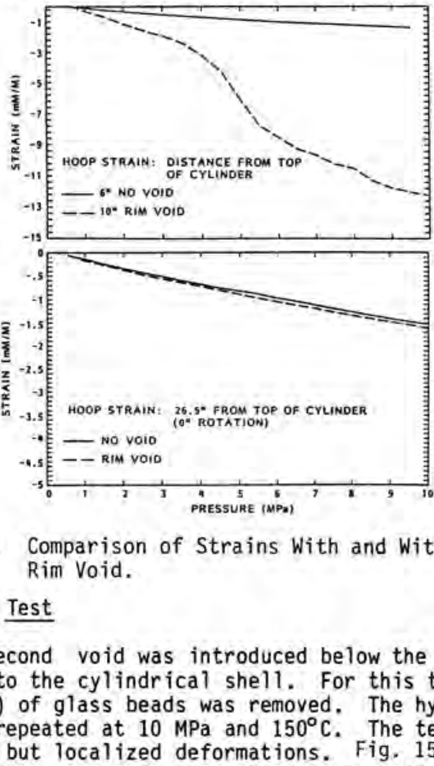


Fig. 16. Comparison of Strains With and Without Rim Void.

## Side Void Test

A second void was introduced below the top lid adjacent to the cylindrical shell. For this test, 1.64 kg (0.7 L) of glass beads was removed. The hydrostatic test was repeated at 10 MPa and 150°C. The test produced large but localized deformations. Fig. 15 shows two buckling waves in the cylindrical shell and the dent in the lid. The container retained its integrity and pressure boundary in spite of the large deformations.

Large, non-linear strains were measured near the void. Away from the void, the strain patterns were close to the results of the previous tests, when there was no void (see Fig. 16).

## POST HYDROSTATIC TEST INSPECTION

## Evaluation of Particulate

After the container was opened, the particulate at the top surface was carefully examined. The grains of particulate were not broken and water did not enter the container. The compressive tests conducted on the particulate used in the prototype showed that :

- At room temperature, the grains of the particulate started breaking down at a compressive stress of above 31 MPa.
- The Young's modulus of elasticity is estimated at 337 MPa. The Poisson's ratio is about 0.41. These values were calculated assuming that linear-elastic formulations for solid bodies are valid for granular materials.

## CONCLUSIONS

The Thin-Walled, Particulate-Packed container has been shown to satisfy all of the postulated requirements, and is a potentially viable option for use in the disposal vault. It has been shown that:

- The container has adequate strength to support the postulated external pressure.
- Good quality of packing can be ensured.
- Container integrity can be retained even if significant voids are present.

The following activities still need to be investigated to fully demonstrate the feasibility of using the container for fuel disposal:

- The feasibility of remotely assembling and handling of the container.
- The adequacy of titanium to resist corrosion for 500 years when large tensile strains are present.

## ACKNOWLEDGEMENTS

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