# Demonstration Test for Transporting Vitrified High-Level Radioactive Waste: Water Immersion Test

*Y. Gomi, C. Ito, O. Kato*
*Central Research Institute of Electric Power Industry*

## INTRODUCTION

The national policy on the nuclear fuel cycle is based on the "Long-Term Plan for Utilization of Nuclear Energy" issued by the Atomic Energy Commission of Japan, and the basic policy on the nuclear fuel cycle is that spent fuel from light-water reactors (LWR) should be reprocessed.

In line with this policy, some spent fuel has been reprocessed overseas, and high-level radioactive wastes (HLW) have been generated by such reprocessing. Some of the high-level radioactive wastes have been returned by sea transport. In order to ensure the safe transport of high-level radioactive wastes, demonstration tests stipulated by the International Atomic Energy Agency (IAEA) transport regulation were carried out in the Central Research Institute of Electric Power Industry. This paper describes the water immersion test. This work was conducted under a contract from the Science and Technology of Japan.

## TEST CASK

The test cask is designed as a Type B package and the design combines the specific structural features of both the COGEMA and the BNFL (planned) casks, which are used for shipping HLW from France and the United Kingdom, respectively.
The specifications and external view of the cask used for the drop test are shown in Figure1.
The cask is characterized structurally as follows:

- The cask body is covered with a neutron absorber enclosed by a thin steel plate.
- The contents of the package, the basket and the HLW canister, and the lid and bottom shock absorbers were removed during the water immersion test.

## TEST METHOD

Test at Water Depth 15 m

The test was conducted at a pressure equivalent to a water depth of 15 m (150 kPa) for 8 hours using the test cask in accordance with the IAEA transport regulations.

Test at Water Depth 200 m

A test was conducted for 1 hour at a pressure equivalent to a water depth of 200 m

(2 MPa) which is applied to spent fuel shipping casks by the IAEA transport regulation, although the test is not applied to packages containing high-level radioactive wastes.

Test at Water Depth of more than 200 m

The IAEA transport regulations do not specify the ability of the cask to withstand the pressure if sunk deeper at sea. Nevertheless, tests were conducted to assess the ability of the cask to withstand such pressures (plastic deformation). The test pressure, as an external pressure which allows identification of the plastic deformation of the cask body, lid and the contact surfaces forming the seal boundary of the cask, is determined to be equivalent to a water depth of 3,000 m (30 MPa) based on the preliminary analytical results.

The ability of the package to withstand deep sea pressure was analyzed using sophisticated techniques, and found to comply with the conservative scenario of an environmental impact assessment for sinking in a deep sea region. In the immersion test, the cask body, bottom plate, and lid plate form part of the pressure structure, and the strain and displacement were measured using strain gauges and displacement sensors in the main part of the cask in order to assess the behavior of the cask under the external pressure. Figure 2 shows the arrangement of the strain gauges and displacement sensors.

A leak test was conducted both before and after the immersion test, and the seal performance of the cask was assessed. The seal part was maintained to a vacuum pressure, and leakage from the seal part and the vacuum pressure were monitored continuously during the test. The test facility consisted of a large pressure vessel of 6 m height and 3 m diameter, and a high-pressure pump was used to apply an external pressure equivalent to a depth of 5,000 m.
The immersion tests were carried out at the Yokosuka laboratory of CRIEPI.

## TEST RESULTS

Figure 3 shows the history of pressure applied to the cask. Figure 4 shows the measured strain and displacement at the main part of the cask versus the test pressure. Table 1 shows the leakage rate of the seal part in the leak test. The results can be summarized as follows.

- At an external pressure equivalent to a water depth of 15 m, the main body part of the cask was slightly strained and deformed. The leak test before and after the immersion test did not show any differences, and the leakage was in the order of $10^{-4}$ atm • cc/s. This leakage rate is satisfactory, and the quantity of leaked radioactive material may be of the order of $10^{-8}$ of the regulatory criteria. The package therefore satisfies the technical requirements of type B packages.

- At an external pressure equivalent to a water depth of 200 m, the measured strain and displacement were sufficiently within the elastic limit. The containment system of the cask between the O-ring was measured continuously under vacuum pressure, and no pressure loss was recorded during the test. The model cask therefore satisfied the container system requirements for spent-fuel packages.

- At an external pressure equivalent to a water depth of 3,000 m, no leakage of the containment system was observed, and seal performance was maintained. The leakage rate before and after the test was of the order of $10^{-4}$ atm • cc/s. At this external pressure equivalent to a water depth of 3,000 m, the strain and displacement of the package body and bottom were within the elastic limit. However, the strain and displacement of the lid plate showed nonlinear behavior, and plastic strain occurred in some parts of the lid, causing permanent displacement after unloading.

## ANALYTICAL MODEL

The general purpose FEM nonlinear analysis code ABAQUS was used for the elastic-plastic analysis of the cask when subjected to the external pressure. The stress and strain of each part of the cask were calculated and compared with the experimental results, and it was shown that the simulation results accurately represented the behavior of the cask when subjected to the external pressure.

Two kinds of analytical models were used, one to determine the behavior of the whole cask, and the other to investigate the behavior of the lid seal part in detail. In view of the shape of the whole cask, two-dimensional axis-symmetric revolution models are used. Figure 5 shows the models used.

The boundary conditions were axis-symmetric, a lid model was used for the interface element, the relative displacement of the contact surface of the union of the lid and the body normal to the surface was used to judge the opening contact surface, and the tangential contact plane was allowed to slide freely.

A plastic model was used with the incremental theorem based on isotropic hardening, assuming the Mises condition. The stress-strain relation was approximated by a bilinear diagram with the yield strength of 0.2% and ultimate strength. Adopting a two-dimensional axis-symmetric model, the volume of the bolts and the lid were calculated and equivalent volume ratio characteristics were used.

## ANALYTICAL RESULTS

### Comparison of Analytical Results with Experimental Results

Based on the loading history during the water immersion test at an equivalent water depth of 3,000 m, pressure loading and unloading were simulated for both the whole model and the lid part model, and the analytical results were compared with the experimental results. In the whole model, the body and the bottom were analyzed, while in the lid model, only the lid was analyzed.

Figures 6 and 7 show the strain of the inner surface of the body and the bottom of the whole model, and the results agreed with the experimental results up to 200 m equivalent water depth, as required by the regulations. The simulation method is thus applicable for evaluating the immersion test of the cask. A comparison of the simulated results with the experimental results also showed good agreement for an equivalent water depth of 3,000 m, which exceeds the regulations.

In the lid model simulation, the strain at the center of the lid under a pressure equivalent to a water depth of 200 m, as required by the regulations, agreed with the experimental results. At an equivalent water depth of 2,000 m, the strain in the lid increased greatly, and after unloading there was residual strain, although the simulation results showed only elastic behavior. Figure 8 shows the stress-strain diagram of the lid material, which is approximated by a polylinear relationship. Figure 9 compares the simulation results with the experimental results for strain versus pressure for the outer surface of the lid, and demonstrates agreement between the two.

### Evaluation of the Pressure with Standing of Actual Packages

Analysis methods were established to simulate the behavior of actual packages used for transport by both COGEMA and BNFL (planned). The packages were evaluated by the analytical code verified by water immersion tests and were found to comply with the transport regulations. A hypothetical accident of a deep-sea sinking that is not specified in the regulations was also investigated in terms of the stress, and the safety of the packages was demonstrated. In the simulation, the conditions used were the same as those in the experimental demonstration test, and to give a conservative estimate, the material characteristics at the maximum surface temperature of the package for real transport were used.

(1) Results for pressure specified in the IAEA transport regulations: Tables 2 and 3 show the simulated results at an external pressure equivalent to a water depth of 15 m and 200 m. The stress in the actual package was less than the critical stress, and the actual package was found to comply with the technical requirements of the safety regulations.

(2) Results for pressure exceeding that specified in the IAEA transport regulations: In the whole cask model analysis at a pressure equivalent to a water depth of 6,000 m, the stress in the actual package in both the main body and the bottom were less than the ultimate stress of the Tresca criteria, except for local parts of the body and the bottom connection. In the lid model analysis, at a pressure equivalent to a water depth of 3,000 m, the lid seal yielded locally at the ultimate stress of the Tresca criteria.

## CONCLUSION

The demonstration test cask was shown to comply with the IAEA transport regulations in the water immersion tests, and a simulation method was established. Deep-sea tests and analyses which are not specified in the IAEA transport regulations were conducted, and the safety margin of actual packages was evaluated.

Table 1 Result of the leak test

| | No. | Test | Start | | Finish | | | Leakage Rate (atm cc / sec) |
|---|---|---|---|---|---|---|---|---|
| | | | Temp. (℃) | Press. (mbar) | Time (min) | Temp. (℃) | Press. (mbar) | |
| Water depth of 15 m | ① | Before | 22.1 | 0.017 | 120 | 21.6 | 3.573 | $2.22 \times 10^{-4}$ |
| | ② | After | 22.7 | 0.016 | 120 | 21.9 | 1.858 | $1.15 \times 10^{-4}$ |
| Water depth of 200 m | ② | Before | 22.7 | 0.016 | 120 | 21.9 | 1.858 | $1.15 \times 10^{-4}$ |
| | ③ | After | 23.7 | 0.015 | 120 | 23.0 | 8.071 | $5.02 \times 10^{-4}$ |
| Water depth of 3000 m | ③ | Before | 23.7 | 0.015 | 120 | 23.0 | 8.071 | $5.02 \times 10^{-4}$ |
| | ④ | After | 24.2 | 0.013 | 120 | 23.7 | 15.505 | $9.62 \times 10^{-4}$ |
| Water depth of 3000 m | ④ | Before | 24.2 | 0.013 | 120 | 23.7 | 15.505 | $9.62 \times 10^{-4}$ |
| | ⑤ | After | 24.5 | 0.014 | 120 | 24.0 | 16.049 | $9.95 \times 10^{-4}$ |

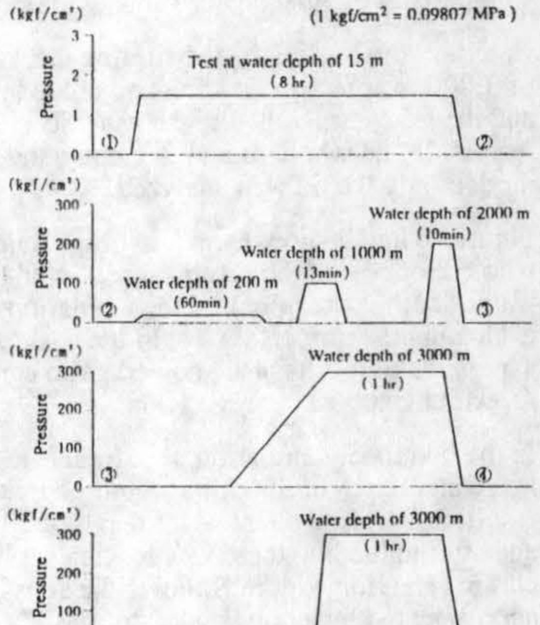


Table 2 Equivalent stress (COGEMA) [MPa]

| Position | | Water Depth of 15m | Water Depth of 200m | Yield Stress (Sy) |
|---|---|---|---|---|
| Body | D1 | 0.7 | 8.7 | 183 |
| | D2 | 0.3 | 4.7 | |
| | D3 | 0.6 | 8.5 | |
| | D4 | 0.3 | 4.5 | |
| | D5 | 0.6 | 8.6 | |
| | D6 | 0.3 | 4.7 | |
| Bottom | S1 | 0.3 | 4.7 | 183 |
| | S2 | 0.7 | 9.6 | |
| | S3 | 0.2 | 2.7 | |
| | S4 | 0.5 | 7.4 | |
| Lid | O1 | 10.8 | 94.2 | 155 |
| | O2 | 5.7 | 66.4 | |
| | O3 | 25.3 | 82.0 | |
| | O4 | 20.2 | 51.5 | |
| | O5 | 39.9 | 66.0 | |
| Contact Point | C1 | 28.3 | 44.0 | 183 |
| | C2 | 23.1 | 55.2 | 155 |

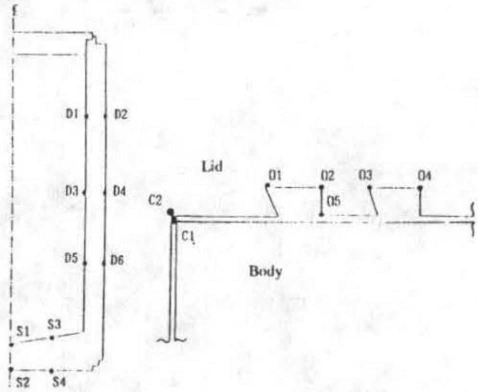
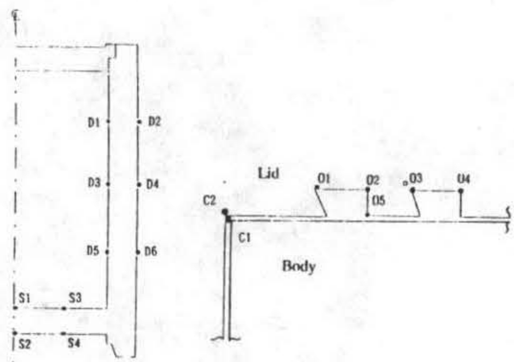
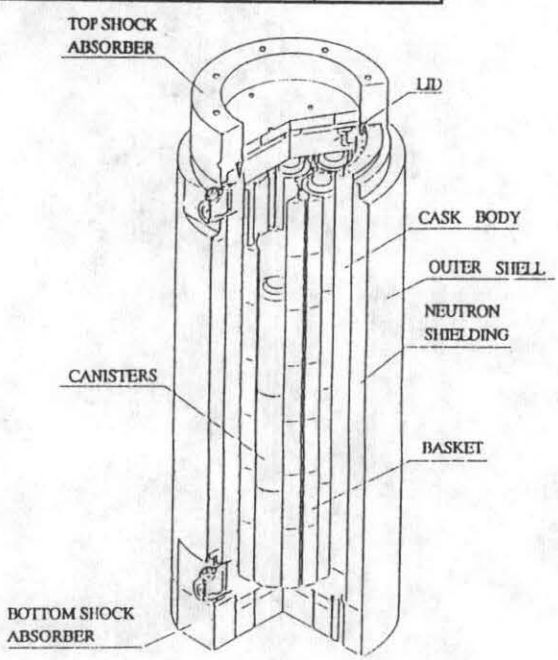



Table 3 Equivalent stress (BNFL) [MPa]

| Position | | Water Depth of 15m | Water Depth of 200m | Yield Stress (Sy) |
|---|---|---|---|---|
| Body | D1 | 0.6 | 7.6 | 183 |
| | D2 | 0.3 | 4.0 | |
| | D3 | 0.6 | 7.8 | |
| | D4 | 0.3 | 3.8 | |
| | D5 | 0.6 | 7.8 | |
| | D6 | 0.3 | 4.0 | |
| Bottom | S1 | 0.3 | 3.4 | 183 |
| | S2 | 0.4 | 5.6 | |
| | S3 | 0.1 | 1.5 | |
| | S4 | 0.2 | 3.3 | |
| Lid | O1 | 15.4 | 58.7 | 131 |
| | O2 | 7.7 | 36.7 | |
| | O3 | 11.8 | 45.9 | |
| | O4 | 7.0 | 24.8 | |
| | O5 | 8.8 | 42.9 | |
| Contact Point | C1 | 13.1 | 56.1 | 183 |
| | C2 | 12.1 | 68.3 | 131 |




SPECIFICATIONS

Total Weigt : 115ton

Total Length : 6800mm

Diameter of Cask : 2400mm
(including outer Cask)

Thickness of Cask Body
: 254mm

Total Number of Canisters
: 28

Quantity of Heat
: 1.46 kW/canister

Fig. 1 Concept and Specifications of Demonstration Test Cask

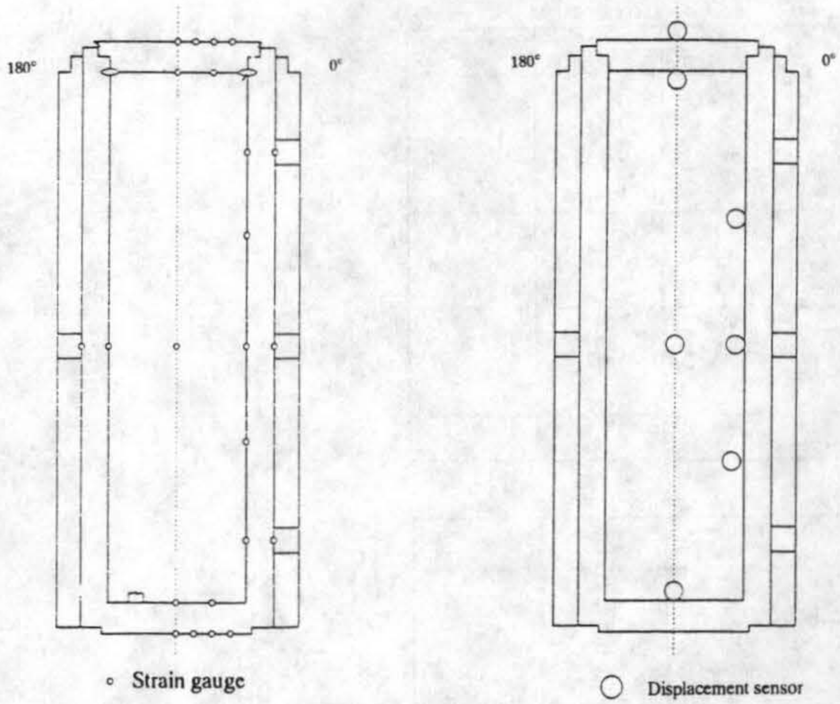



Fig. 2 Arrangement of the strain gauges and displacement sensors

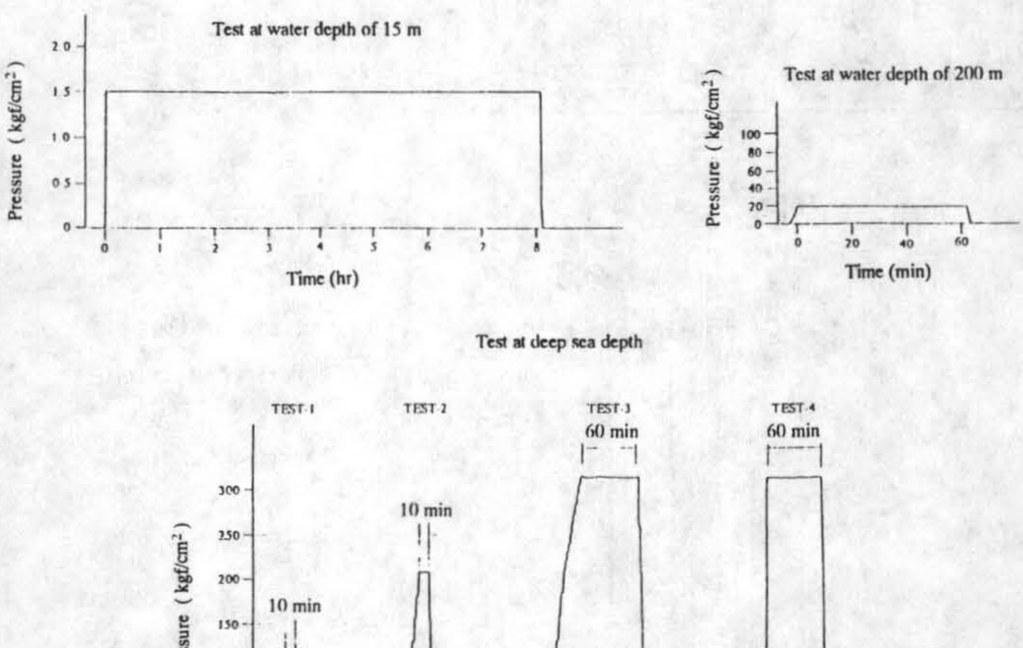



Fig. 3 History of pressure applied to the cask
(1 kg/cm$^2$ = 0.09807 MPa)

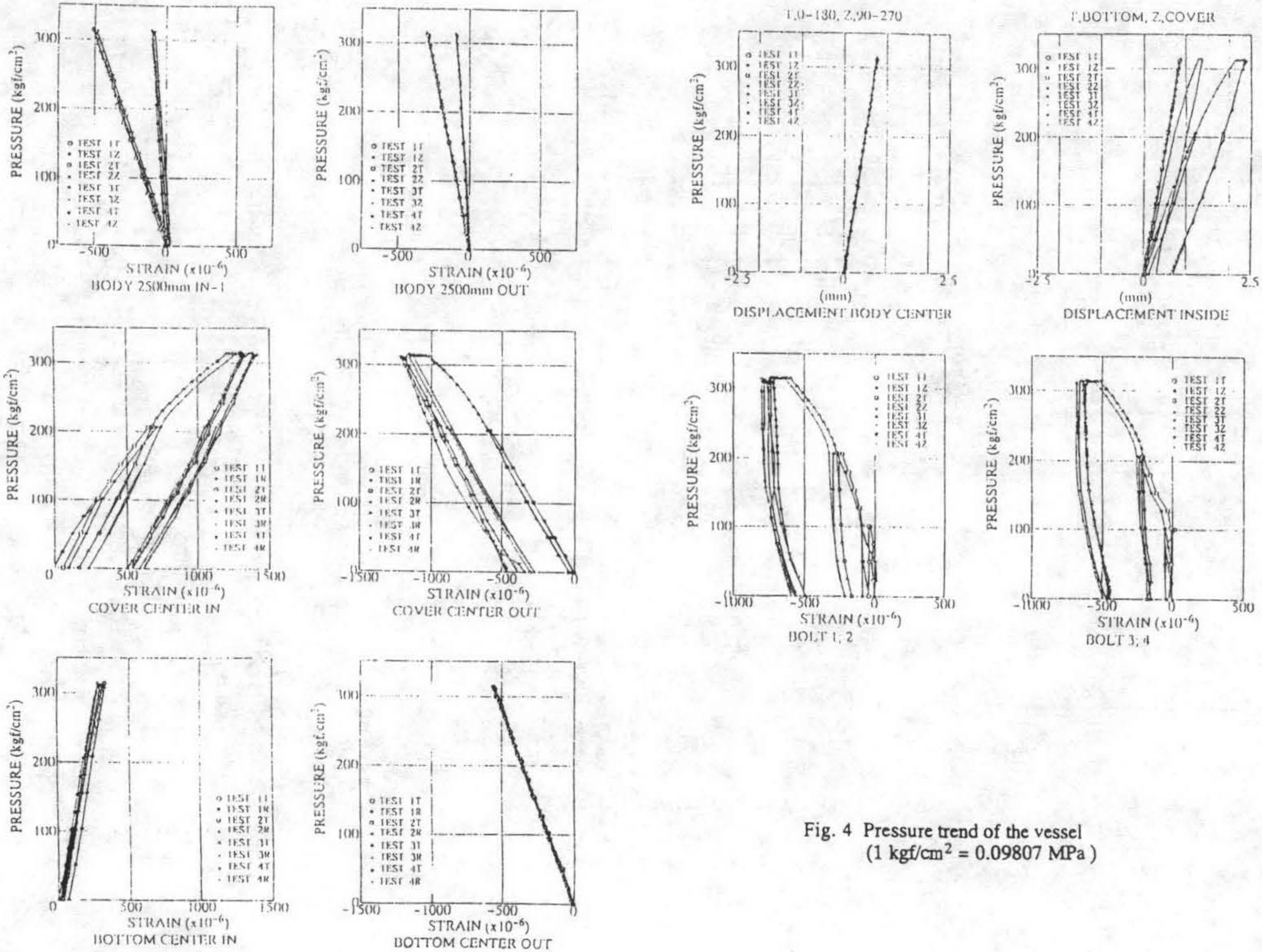



Fig. 4 Pressure trend of the vessel
($1\ kgf/cm^2 = 0.09807\ MPa$)

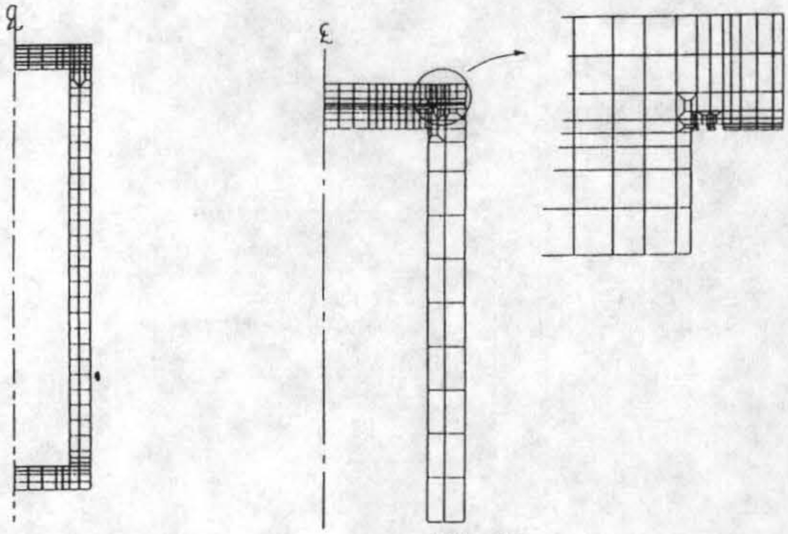




Fig. 5 Analytical models

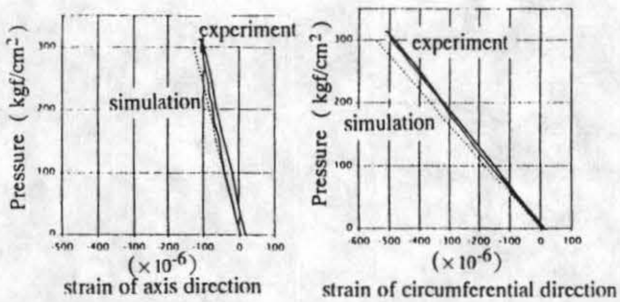




Fig. 6 Strain of the inner surface of the body
(1 kgf/cm$^2$ = 0.09807 MPa )

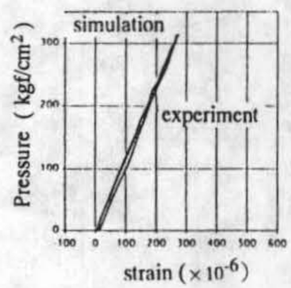




Fig. 7 Strain of the bottom (center)
(1 kgf/cm$^2$ = 0.09807 MPa )

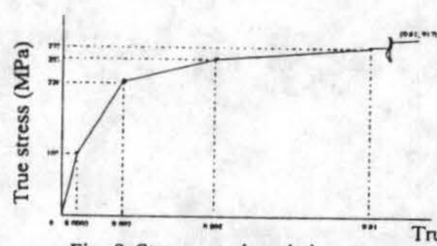




Fig. 8 Stress - strain relation

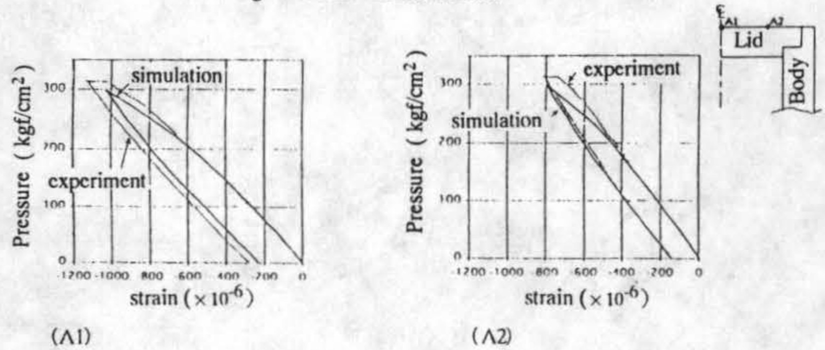




Fig. 9 History of strain (Lid)
(1 kgf/cm$^2$ = 0.09807 MPa )