Analysis of the HCDA -- Simulation in a 1/6th-Scaled Model of the SNR-300 with the SEURBNUK-2 Code

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Summary

Coupled fluid dynamics/structural mechanics codes are used extensively in the analysis of containment loading following an hypothetical core disruptive accident in a liquid fast breeder reactor. Experimental programmes devised to validate these codes should include scaled models that closely resemble real reactor geometries. Realistic large fluid and structural displacements should be considered in order to ensure that the integrity of the reactor vessel is adequately demonstrated.

The SNR 300 1/6th-scaled model test performed at JRC Ispra in the year 1976 produced strains in the outer tank of only 0.4 per cent. This was thought insufficient to adequately analyse the complex fluid/structure interaction processes, and the same vessel has been used in a repeat test designed to produce permanent straining of more than 3 per cent. As the shield tank used for the original shot had yielded by 2 per cent, this was replaced for the repeat test.

The test vessel is cylindrical with a hemi-spherical bottom, stands 2.55m high, is of diameter 1.1m and thickness 10mm - the shield tank is now 4mm thick (compared to 8mm in the original test). Other internal components include a dip plate suspended from a rigid roof plug and a thick perforated diagrid which supports an inlet plenum. The diagrid itself is held in place by a cylindrical support skirt attached to the hemisperical base of the tank. For the second shot fired in the year 1979 a new pyrotecnic charge was manufactured and calibrated at the JRC Ispra. Many gauges recorded pressures, strains and displacements at various locations within and external to the vessel.

The hydrodynamics/structural mechanics code SEURBNUK-2 is now developed jointly by AEE Winfrith and JRC Ispra for the analysis of containment loading following an HCDA. The code utilizes an Eulerian finite difference approach and incorporates an implicit calculation of compressible fluid flow, a generalized representation of bounding surfaces and the computation of the response of thin plates and shells.

This paper describes the SEURBNUK-2 calculation of the 1/6th-scaled model and comparisons made between the experimental and calculated results.

A recent improvement to the code is the inclusion of deforming perforated plates and shells. This new facility enabled the flow through the dip-plate, diagrid and diagrid support collar to be adequately described, whilst maintaining a fully interconnected structural representation of the internal components.

A calculation run time was chosen so that most of the major loading events of the experiments had taken place. The results describe qualitatively all the salient physical phenomena recorded during the experiment. Globally, the calculated dynamic behaviour of the system depicted by strain and pressure time histories, is in satisfactory agreement with the experimental data, however, the code cannot be expected to reproduce the detailed effects in close proximity of the diagrid and dip-plate because of the distributive resistence model used in the computation.

The capability of the SEURBNUK-2 code to follow adequately the loading phenomena in a reactor geometry under accident conditions is demonstrated.

1. Introduction

As part of the formal licensing procedures for the SNR-300 prototype fast reactor, an examination is necessary of the loading to the primary containment under Hypothetic Core Disruptive Accident (HCDA) conditions. The study involves full-scale reactor accident simulations using large computer programs, and to validate the codes, a series of scale-model experiments of geometric similarity. Two such experiments for the SNR-300 reactor have been carried out at 1/6th scale at the Joint Research Centre (JRC) Ispra.
The first test in 1976 produced permanent maximum strains in the primary vessel of only 0.4 %, but in the second test, fired in April 1979, a thinner inner tank was used and plastic strains in excess of 3 % were foreseen. In the event the maximum permanent deformation of the outer vessel was 2.3 %, but this is considered adequate for code validation purposes.
This article describes the numerical simulation of the second 1/6th scale model experiment using the coupled hydrodynamics/structural mechanics code SEURBNUK-2 /1, 2, 3/ developed jointly by the Atomic Energy Establishment (AEE) Winfrith and JRC Ispra. Results are presented in the form of pressure and strain histories at selected gauge positions (80 gauges were used in the test) and these are compared with the corresponding experimental data.
A description of the experimental test assembly is given in section 2. The structural members considered to be of primary significance in a mechanical description of the loading events include the hemi-spherical test vessel, shield tank, perforated dip-plate and diagrid, inlet plenum and diagrid support skirt. These components are described fully in the text. In section 3 a brief description of the SEURBNUK-2 code is given. The present calculation has benefitted from a number of recent improvements to the code including the addition of perforated deforming structures /3/, a multifluid cell capability and an enhanced treatment of the joints connecting different components. Details of the run are presented in the next section, Section 4. A calculation of 6 msec was chosen in order to include most of the major loading events recorded during the experiment. Mesh plots are given at 1 msec intervals which depict the development of the charge bubble, the bulk fluid motion and the deformation of the structural components. A critical analysis of the results is undertaken in section 5 and a summary of the conclusions is reached in section 6.

2. Experimental Vessel Assembly

The containment comprises a stainless steel cylindrical tank with a hemispherical base, stands 2,55 m high (including the plug), is of external diameter 1.1 m and thickness 10 mm. A flange at the top of the tank locates with a support ring bolted to a massive base structure via six strong support columns, see figure 1. The internals comprise a shield tank 1.14 m high and thickness 4 mm bolted to the inlet plenum shell and diagrid.

The diagrid itself is 70 mm thick and is perforated over its central section to allow fluid flow from the core region to the plenum; the perforation ratio is 5 %. Above the shield tank just below the undisturbed water level is a perforated dip-plate (thickness 40 mm, perforation ratio 21 %) suspended from the roof plug by a ring at its edge, and strengthened by a central pillar. The other internals are connected via the inlet plenum shell to an internal flange welded to the hemispherical base of the primary vessel. Both piezo-electric and tourmaline pressure transducers were used as well as high elongation strain gauges. The tolerances for the recording devices, including errors in the data acquisation system, are estimated to be up to 9 % for peak pressure measurements, ± 5 % for impulse data and ± 4 % for the strains. An 8 kg Belgo Nucleaire pyrotechnic charge, intended to produce strains up to 16 % in the internal tank, was used as energy source. The p-v relationship for the charge was determined from five pre-shot calibration experiments, and is drawn in figure 2.

Static loading tests have been performed to obtain uniaxial stress-strain relationships for the main tank, diagrid support, inlet plenum, dip-plate, dip-plate support ring and central support column. In addition dynamic loading tests were undertaken for the main tank, shield tank and hold-down bolts.

The stress strain curves under dynamic loading for the internal and external tanks are reproduced in figure 3; the appropriate strain rate, for the present model is $\dot{\varepsilon} = 10\ sec^{-1}$ for the inner tank and $\dot{\varepsilon} = 4\ sec^{-1}$ for the outer tank. The outer tank only slightly deformed during the first shot (maximum 0,4 %) was used again in the second experiment. All other parts with permanent deformations from the first experiment, i.e. the shield tank, the dipplate and the hold-down bolts, were replaced for the second shot.

3. The SEURBNUK-2 Code.

The SEURBNUK-2 computer code is developed jointly by IRC (Ispra) and AEE (Winfrith) for use in containment loading analyses for fast breeder reactors. A full description of the code, its capabilities and validation programme is given elsewhere /1/, /2/, /4/, and the discussion here concentrates on recent improvements of direct relevance to the SNR 1/6th model test calculation.

Briefly, SEURBNUK-2 is a two-dimensional fluid dynamics code based on the ICE technique of Harlow and Amsden /5/, /6/. A full thin shell treatment for tanks and plates of arbitrary shape is included. A representation of rigid immovable perforated plates has been available in SEURBNUK-2 for some time, /2/, and has proved a useful commodity in the description of the fluid motion relating to porous structures. From the viewpoint of structural response the usefulness is limited as the pressure loading across the plate is not transmitted to the supports because of the rigidity assumption.

A recent improvement to the code is the provision for movable, deforming perforated plates and shells. This new facility is utilized in the modelling of the dip-plate, diagrid and diagrid support to maintain structural interconnectivity.

The pressure drop across the plate is of the form suggested by Smolderen et al /7/:

$$\Delta p = \xi' \rho \frac{\partial w}{\partial t} + \frac{1}{2} \xi \rho \, w|w| \qquad (1)$$

in which ξ' is an equivalent length based on inertia considerations, /7/, /8/ and ξ a dimensionless friction coefficient, /9/. The w used in the formula is the superficial normal velocity of the fluid relative to the plate. For a given perforation ratio, equation (1) relates the velocity of the fluid through the pores to the instantaneous pressure drop across the plate. The difference in pressure on the two sides leads to flexural response from the plate according to

$$\Delta p = \sigma \frac{\partial u}{\partial t} + F_n \qquad (2)$$

in which σ is the mass of the plate per unit area, u the normal velocity of the plate and F_n the restoring force due to the internal material stresses. Equation (2) is integrated within the thin shell processor in SEURBNUK-2 in much the same way as for an impervious plate. Once the plate velocity is known, the normal velocity of the velocity of the fluid through the pores is recovered from equation (1). The fluid-structure coupling is thereby completely specified. The junction points 8,9 and 17 marked in figure 4 (b) consist of three connecting limbs each of which is a Lagrangian thin shell boundary. The disposition of these boundaries as they distort with respect to the underlying Eulerian mesh can lead to situation in which a calculational cell contains three non-connected fluids. To correctly load the sides of the three connecting shells with pressures from the appropriate fluids entails very intricate logical manipulations within the code. Considerable programming effort was necessary in order that multi-component junctions be represented for arbitrary orientation. There is provision for the joints to be hinged (type 3) or to possess rotational strength (type 13). Due to the characteristics of the weld each of the junctions 8, 9 and 17 are modelled as type 13. The calculation presented is without doubt the most complex SEURBNUK-2 simulation to date.

4. Details of the Calculation

Of all the factors affecting the containment loading, it is widely accepted that the energy yield of the source is the most influential parameter. For the SNR 300 1/6th model experiment a reference equation of state for the charge was derived by Belgo Nucleaire from a series of five calibration shots. Two notionally identical charges were manufactured for the 1/6th model test with the duplicate being fired in the calibration device just before the firing of the test proper, as a cross-check on the calibration procedure.

The p-v relationship for the charge so determined is shown as curve I in figure 2. This relation was adopted for a preliminary SEURBNUK run as well as for other codes, but the results from the calculations were all the same. The maximum permanent hoopstrains for the inner and outer tanks were overpredicted by a factor two compared to postexperimental measurement. Much better agreement had been forthcoming for the first 1/6th model test performed in 1976.

It is concluded that the charge is not well characterized in the second test. As mentioned in section 1, the shield tank was thinner for the second test in order to produce larger permanent strains. However, it is now believed that the yielding of the shield tank interfered with the deflagration of the pyrotechnic charge, an effect not represented in the calibration tests where the shielding was much stronger.

It is evident therefore that the characteristics of the energy released need to be redefined. One approach would be to retrace the p-v relationship from the experimental records using containment codes by what amounts to a rather inexact numerical variational technique. This approach is not adopted here. Rather a p-v relationship is defined initially and the SEURBNUK code used to describe in general terms the principal loading events recorded during the experiment. The authors are aware that the simulation now falls short of a stringent code validation exercise, but does serve to demonstrate the capability of the code to handle complex geometries and to reproduce qualitatively the loading histories.

The initial configuration used for the calculation is shown in figure 4. In comparison to the experimental arrangement, figure 1, some differences are apparent. No account is taken of the possible motion of the support columns. The hold-down bolts and the outer tank share, in the calculation, a common fixed point. The diagrid support collar is assumed to be a simple cylinder, the step at the point of attachment with the outer tank being ignored. The slots in the support are modelled in detail however, as the depressurization of the region beneath the inlet plenum affects the loading to the base of the primary tank.

The dip-plate, which is perforated, is supported centrally and at its edge by cylinders of the correct strength but which offer no resistance to fluid flow from the inner to outer regions. To aid efficiency in running the calculation, the thick roof and diagrid structures are modelled as thin shells of the correct masses, but enhanced densities and stiffness.

The outer vessel, which was permanently set by up to 0.4 % after the first experiment, is assumed completely restored for this calculation. The possibilities of variations in thickness, departures from axial symmetry and work-hardening effects are ignored, and the strengthening effect occasioned by the presence of the six inlet and outlet nozzles is likewise neglected. None of the shortcomings in the model are thought to be significant.

5. Critical Analysis of the Results

From the 80 pressure and strain gauge measurements made during the experiment, a selection is taken from certain key locations for comparison with calculated values. Thus for example, in figures 6, 8, 9 are presented pressure/impulse histories for the inner surfaces of those structures surrouding the charge, and in figure 7 that for the outer tank at charge height. One feature is obvious: the smearing of the calculated pressures compared to the experimental. The rise to peak pressure occurs early but the amplitude of the pulse is reduced. This behaviour is characteristic of Eulerian containment codes such as SEURBNUK in which the discretization formulae adopted incorporate a degree of numerical diffusion.

Again, at later times there is further evidence of smoothing the calculated values, especially among the high frequency pulses. However, the integrated effects represented by the mean pressures and impulses compare well, and the records for the inner structures show particularly good agreement. The thin-shell strains shown in figures 10-13 are a direct consequence of the applied pressure loads, the material data, and elasto-plastic properties adopted. It can be seen in figure 10 that there is satisfactory agreement between calculation and experiment for the hoop strain in the inner tank at charge height, but the meridional strain is overpredicted by 75 %. This discrepancy had been noted before with other numerical simulations of experiments involving open cylinders clamped at one end. For this geometry the calculated strong contraction seen in figure 10 seems reasonable, but there is no doubt about the accuracy of the measured data. A possible explanation is that a material under dynamic loading does not follow the recognized von Mises yield criterion and Prandtl-Reusz flow rule used in SEURBNUK. Certainly, any inadequacies in the plastic flow model used will be first apparent in the axial strains where the curvature effects are greatest. More effort is required in this area.

The hoop and meridional strains calculated for the primary tank are in very good agreement with the measured responses, see figure 11. Also there is good qualitative agreement for the strains in the diagrid support structure, serving as an indicator of the loads transferred to the hemi-spherical base of the vessel. This can be seen in figure 12. Again, figure 8 shows that the load experience on the underside of the dip-plate is well predicted. The under-estimated strains for the hold-down bolts evidence in figure 13 appear to be inconsistent and probably reflect inadequacies in the behaviour of the charge and the modelling of the roof structure. The mesh plots in figure 14 depict the growth of the high pressure bubble and the resulting flow field. After early pressurization of the inlet plenum, the fluid movement downwards through the perforated diagrid is quickly stemmed and the main fluid flow is then upwards towards the roof plug. The velocity vectors identify a sensitive flow region between the end of the dip-plate and the top of the inner tank.

The deformations of the inner and outer tanks as a function of height are given in figure 15 and compared with the experimental values. The calculation is terminated at 5.5 msec, when the water rises to the underside of the pug. Clearly there will then ensue further straining, particularly in the hoop direction for the inner tank, but the additions are of minor interest. The problem time is far too short for the determination of the elongation of the hold-downbolts. At the time of writing a new flexible roof treatment is planned for SEURBNUK that is to include the effects of slug impact. It will then be possible to extend the present calculation.

6. Summary and Conclusions

The results of the SEURBNUK post-shot calculations of the SNR 300 1/6th scale model test show in all significant points a reasonable, and sometimes very good, agreement with experimental results. The largest uncertainty is the assumed equation of state for the charge, which appears to have behaved differently in the test from that recorded during the several pre-shot calibration tests. However, the ability of SEURBNUK to treat complicated reactor geometries, including large relative fluid motions and high tank strains, has been adequately demonstrated.

ACKNOWLEDGEMENT

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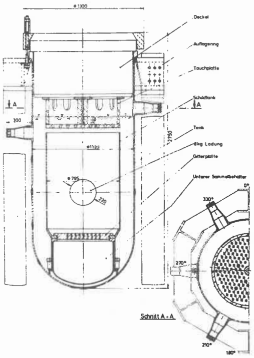


Fig. 1 1/6-Model of the SNR-300

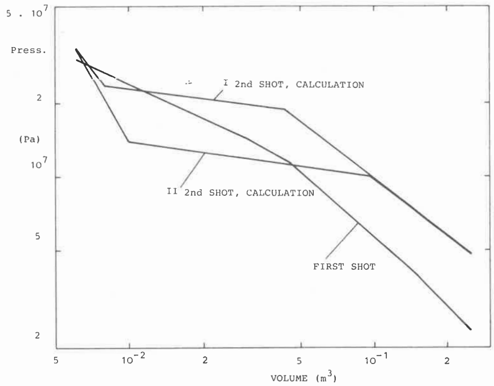


Fig. 2 Pressure-volume relation for the charge

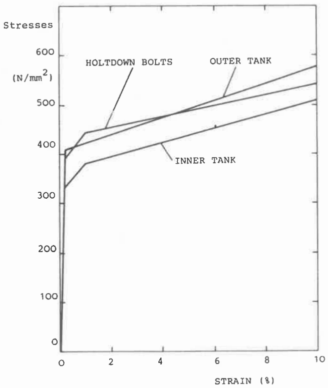
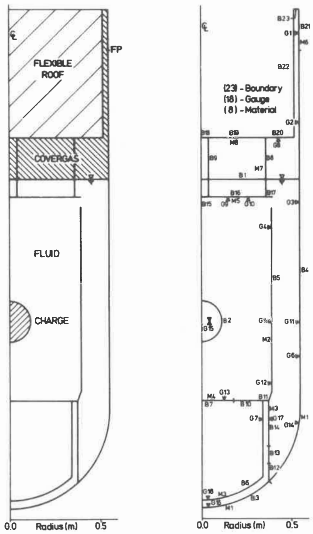


Fig. 3 Strain-stress curves



4a 4b

Fig. 4 SEURBNUK-Model of the 1/6 experiment

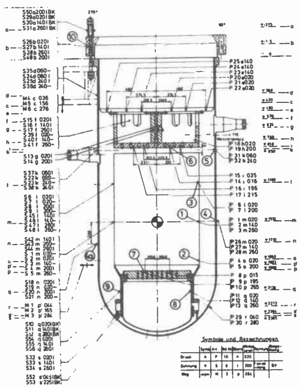


Fig. 5 Location of the gauges

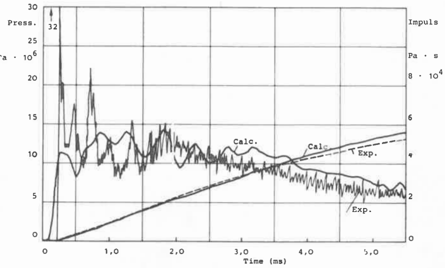


Fig. 6 Pressure, inner tank, charge height

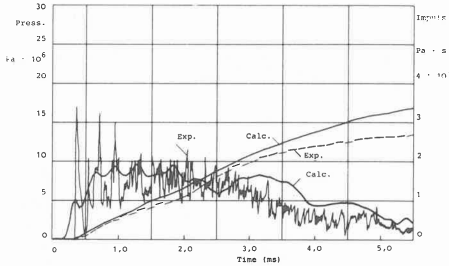


Fig. 7 Outer tank, charge height

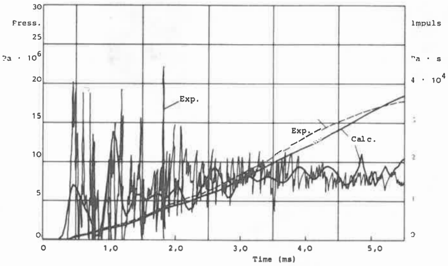


Fig. 8 Pressure, under dipplate

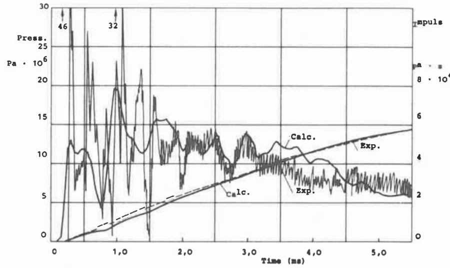


Fig. 9 Pressure, diagrid upper side

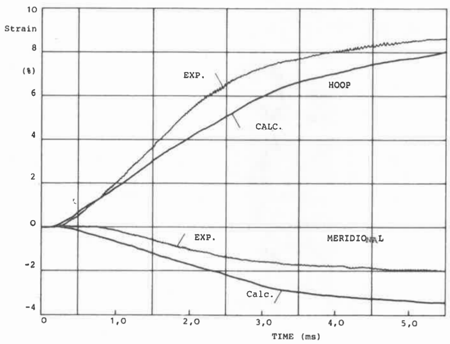


Fig. 10 Inner tank, charge height, hoop and meridional strain, Point 1

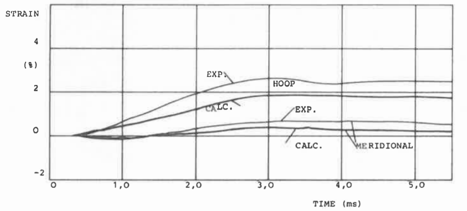


Fig. 11 Outer tank, under charge level hoop and meridional strain, Point 4a

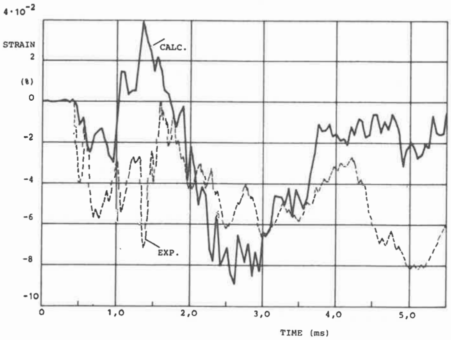


Fig. 12 Diagrid support, meridional strain, Point 9

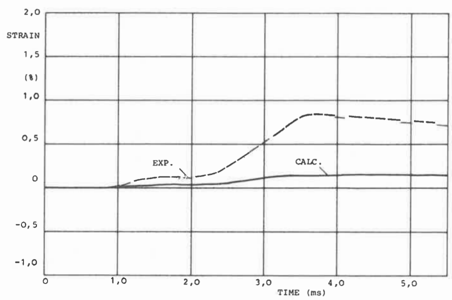


Fig. 13 Holddown bolts, meridional strain, Point 10

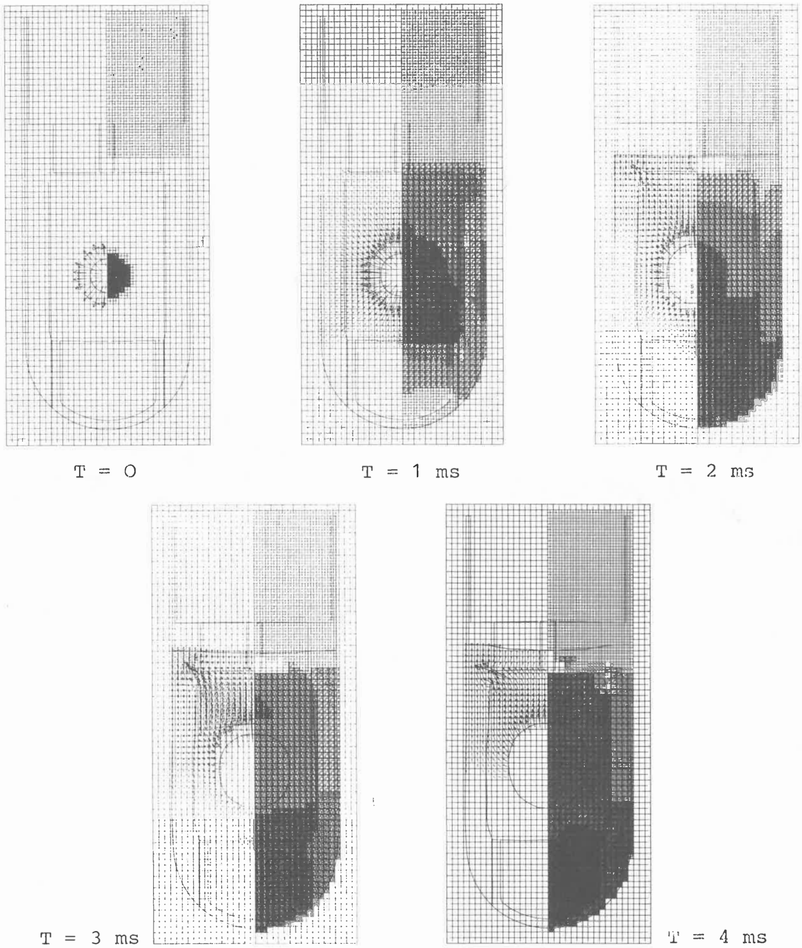


Fig. 14 Meshplots of the SEURBNUK calculation

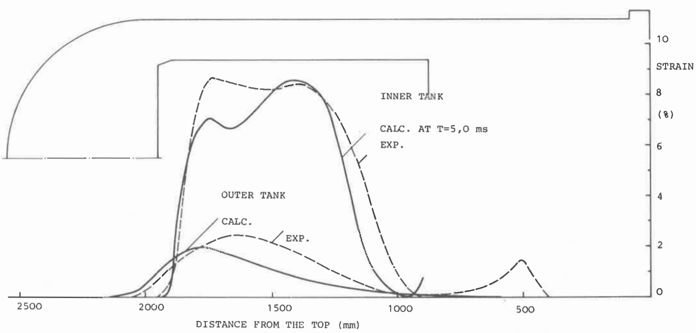


Fig. 15 Final hoop strain of the inner and outer tank