EXPERIMENTAL VALIDATION OF THE CONTAINMENT CODES ASTARTE AND SEURBNUK

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The fast reactor containment codes ASTARTE and SEURBNUK are being validated against experimental data from the COVA series of experiments being performed jointly by the UKAEA and JRC Ispra. The COVA experiments consist of a series of well instrumented small scale experiments providing high quality data of the loads and strains occurring when a well characterised low density explosive is fired under water within a containment vessel. The experiments progress from simple bare vessels to tests incorporating models of the main axisymmetric features of the fast reactor. Two heights of vessel are used providing vessel aspect ratios characteristic of pool and loop reactor types.

The experimental programme is well advanced and the tests fired to date feature internal structures with (i) rigid and deformable internal tanks (ii) perforated and solid diagrids (iii) perforated dip-plates and above core structures and (iv) stacked rod arrays simulating neutron shields.

The experiments are not yet complete and more analysis remains to be done but examples from the later tests are presented to illustrate the effect of some internal structures on the containment loading.

Validation of ASTARTE and SEURBNUK is a continuing process. Progress with this work is reported under the following headings:-

<u>The modelling of thick containment vessels</u>
Calculations for some early COVA tests are reported to demonstrate the importance of modelling the elastic response of the thick overstrong containment vessels.

<u>Experiments with deformable outer vessels</u>
Calculations for COVA tests featuring thin outer vessels are presented to show the codes' current ability to calculate deformations for a variety of vessel geometries and end conditions.

<u>Experiments with internal structures</u>
The later COVA tests feature internal structures which are representative of reactor geometries. The ability of the codes to deal with internal structures is illustrated by calculations performed for two of the more complicated tests which show many contrasting features.

<u>Experiments with permeable structures</u>
Several of the experiments include permeable internal structures (eg diagrids, dip-plates and neutron shields). A facility is incorporated in SEURBNUK for representing fluid flow through structures of this kind submerged in the fluid. Calculations for a selection of these experiments illustrate that SEURBNUK is able to reproduce the main fluid flow patterns and pressure drop characteristics of these experiments.

<u>Prediction of Roof Loadings</u>
The loading of the reactor roof structure as a result of fluid impact is a topic of particular interest and results are presented which show that SEURBNUK predictions of roof pressures are generally a marked improvement on previous ASTARTE predictions.

Results for both codes are compared with measured data from the COVA experiments in the form of final strain profiles and the dynamic records of pressure and impulse at specific measuring positions. The results presented suggest that the codes can be used effectively for containment studies though further analysis is needed to improve code predictions of vessel deformations and roof loadings.

1. INTRODUCTION

The fast reactor containment codes ASTARTE (1) and SEURBNUK (2) are being validated against data from the COVA series of small scale experiments (3) in a programme being performed jointly by the UKAEA and JRC Ispra. The experiments progress from simple bare vessels to assemblies incorporating the main axisymmetric features of loop and pool type reactor designs: water is used to simulate the sodium coolant and a well characterised low density explosive (4) provides the energy release. The experimental programme is nearly complete and recent tests have featured internal components including rigid and deformable inner tanks, perforated and solid diagrids, stacked rod arrays (modelling neutron shields), perforated dip-plates and above core structures. The aim of this validation programme is to establish that these codes adequately model the pressure wave propagation, fluid flows and deformation of internal structures that result from an internal energy release, and hence to establish the validity of their use for assessment of the resultant loading on the primary containment.

The main developments in SEURBNUK since the last review (4) include the provision of a treatment for perforated plates and permeable structures and an enhanced structural response capability provided through a link to the finite element code EURDYN (5). ASTARTE developments include improvements in the treatment of internal shells and elastic-plastic materials and the implementation of a mesh rezoning scheme for use when severe mesh distortion occurs. The validation of the codes is a continuing process and work since the last review has tended to concentrate on SEURBNUK. Progress is reported under several specific topic headings which highlight some important aspects of the validation programme, and calculations are presented for a selection of the later tests with complex internal structures.

The tests mentioned in the presentation are shown in figure 1. The vessels are partly filled with water, leaving an air gap, and the spherical low density charge is positioned on the central axis.

2. EXPERIMENTS WITH THICK CONTAINMENT VESSELS

ASTARTE and SEURBNUK calculations were reported in the last review for COVA tests with thick outer vessels and no internal structures. In these tests, the first pressure pulse registered on the vessel floor arises from the pressure wave direct from the charge and this is followed by waves reflected from the vessel wall. The results showed that both codes were over-predicting the component due to the reflected wave, by as much as 50% in some cases.

Various reasons for the discrepancy have been put forward including the possibility that the 4 cm thick vessel (though overstrong) might not be completely rigid. Some recent work (6) has suggested that elastic deformation of the vessel could temporarily extract a significant proportion of the energy in the incident shock wave and delay releasing this energy for a time comparable with the time needed for pressure pulses to cross the model.

A number of calculations have been performed to provide a test of this hypothesis. Instead of representing the thick outer tank as rigid it has been modelled in ASTARTE and SEURBNUK calculations as a thin shell of thickness 4 cms. It is not suggested that this is the preferred representation of the tank; the aim was to provide an inexpensive and practical test of the importance of the elastic response of the vessel in the correct 2-D geometry. Calculations were performed for the bare vessel tests FT4 and WT5.

Figure 2 illustrates the marked improvements that are achieved in predicted pressures when the response of the thick vessel is modelled; it compares ASTARTE predictions with the measured data for a typical floor position in the long tank experiment WT5. In the original calculation which used a rigid vessel model the reflected pressure wave was overestimated, later waves were underestimated and a final pressure pulse was completely absent. In modelling the response of the vessel, a dramatic improvement is achieved in both the reflected wave and the later waves which are now in good agreement with the measured data; the missing final pulse is also present.

With the rigid tank representation cancellation of errors in predicting the individual pressure waves resulted in good agreement ($8 \pm 1\%$) with the measured final impulses; even better agreement ($5 \pm 1\%$) is achieved with the improved calculation.

3. EXPERIMENTS WITH DEFORMABLE CONTAINMENT VESSELS

ASTARTE calculations for a selection of tests with deformable outer vessels were reported in the last review. Since this review a number of SEURBNUK calculations have been performed and the ability of both codes to calculate the deformation of outer containment vessels can now be assessed.

For the tests with external cylindrical deformable vessels both codes consistently underestimate hoop strains in the lower part of the vessel by about 35% and substantially overestimate hoop strains near the top, although qualitatively, the profile has the right shape. The axial strains are fairly well predicted except near the top where there is a significant overestimate of the comparatively small measured strains and for the stress-strain model incorporated in the codes this is consistent with the overestimate of hoop strain in this position; see figure 3.

In the hemispherically bottomed vessels hoop strains are again overestimated near the top but axial strains do not correlate well with the measured values. The relationship between the hoop and axial strains is often poorly reproduced, (figure 3).

The measured pressures recorded on a thin vessel show that an initial sharp pulse which accelerates the vessel is followed by a low pressure plateau corresponding to the yield pressure of the vessel. Both codes diffuse the initial sharp pulse into a low broad pulse but qualitatively the following pressure plateau is well predicted by SEURBNUK. In contrast ASTARTE is representing this low plateau as a series of spikes (4).

In general the errors in the total impulses on the vessel wall do not seem to be well correlated with the errors in the final strain. For example, the impulses are well calculated for the short cylindrical vessel test (WT6/FT6) but are clearly underestimated for the long cylindrical vessel test (WT8/IT7) although the hoop strain is substantially underestimated in both cases.

In searching for the causes of the discrepancies between the calculated and measured strains uncertainties in the material data defining the steel used for the vessels have been considered. However, some check calculations have been performed to determine the sensitivity of predicted strains to variations in material data and it seems unlikely that data uncertainties could completely explain the discrepancies.

Investigations are also underway into other aspects with particular emphasis on the shell theories, coupling of fluid and shell, material models and the general prediction of hydrodynamic loadings. Though SEURBNUK and ASTARTE predictions compare favourably the discrepancies with the measured data have not yet been resolved. Further details of this work are presented elsewhere in this conference (7).

4. EXPERIMENTS WITH INTERNAL STRUCTURES

The ability of the codes to deal with internal structures is illustrated by calculations performed for two of the more complicated tests which show many contrasting features. These tests represent the simplest geometries in two series of experiments with increasingly complex internal structures:-

WT11: Long (loop type) geometry, large cover gas gap, thick outer vessel, floor supported diagrid, thin inner vessel.

FT13: Short (pool type) geometry, small cover gas gap, thin outer vessel, wall supported diagrid, no internal vessel.

In WT11 events depend mainly on pressure wave and fluid motion interactions with generally fairly rigid structures whereas the FT13 test involves a number of interacting deformable components and events are influenced by the larger structural movements possible.

An initial ASTARTE calculation for WT11 was discussed in the last review; the solid diagrid was modelled as an elasto-plastic material so that pressure wave transmission and diagrid deformation could be represented. In general, the results indicated that ASTARTE was able to follow the early events of the experiment although inadequacies in the modelling of the internal vessel, together with severe mesh distortion at the top of the internal vessel, made the calculation unreliable during the later phases. Subsequently a calculation has been performed with a full thin shell treatment for the internal vessel and a fluid-shell coupling which allows free fluid slip over both surfaces of the shell (7). A more realistic straining of the internal tank is obtained for this calculation although some mesh distortion still occurs at the top of the tank, figure 4.

The problems in ASTARTE associated with mesh distortion and relative fluid flows do not occur with SEURBNUK. An epoch from a SEURBNUK calculation for WT11, illustrating the shear flow at the top of the internal vessel, is shown in figure 5. For this calculation the diagrid was represented as a rigid structure although an improved representation using a thin shell model or the SEURBNUK-EURDYN link would be possible.

Figure 6 shows a comparison of the pressure profile calculated by SEURBNUK and the measured profile at a position on the floor; SEURBNUK is reproducing all the main features of the pressure profile although the calculation does not represent the small initial pulse corresponding to the shock wave transmitted through the diagrid. Both ASTARTE and SEURBNUK are able to provide a satisfactory prediction of the events in the lower regions of the vessel. However, neither code appears to be able to reproduce the pattern of pressures on the roof and roof impulses are significantly overestimated as reported in section 6.

For FT13 only SEURBNUK is able to represent the junction between the outer vessel and the diagrid support collar and the fluid flow through slots in this collar. For a first calculation, the diagrid was represented as a rigid structure and an epoch of this calculation is presented in figure 7. The figure illustrates the restraining action of the rigid diagrid and support collar on the straining of the outer vessel. The calculation reproduces most of the important events of interest but focusses attention on the need for an accurate modelling of the forces at the stiff, welded junction of the support collar and outer vessel and, in contrast to WT11, on the importance of modelling shock transmission through the diagrid. The link between SEURBNUK and EURDYN provides the means for modelling diagrid response and a calculation demonstrating the use of this recently developed option for a case with geometry similar to FT13 is reported in reference 5.

Work is continuing to improve the representation of the structural features in FT13 and to explain the poor predictions of roof loading in WT11 but the calculations illustrate that SEURBNUK is capable of modelling the main aspects of these experiments which have contrasting internal features. The results are encouraging and, together with the calculations discussed in the next section for tests with permeable internal structures, suggest that SEURBNUK will be able to provide adequate calculations for fairly complex experimental and reactor configurations.

5. EXPERIMENTS WITH PERMEABLE STRUCTURES

Several of the COVA tests incorporate permeable internal components which model perforated dip-plates, perforated diagrids and neutron shield arrays. A method has recently been developed and incorporated in SEURBNUK for the treatment of fluid flow through resistances representing such permeable components (5). In brief, the SEURBNUK option uses a distributed resistance method and involves the introduction of momenta sink terms in the momentum equations. The extra pressure drop across a complete Eulerian cell, due to the resistance, is assumed to be of the form of a steady state pressure loss term. At present two options are provided in the code, a fixed grid resistance coincident with an Eulerian mesh line and a fixed volume resistance assigned to a block of Eulerian cells. For a volume resistance the blockage effect of the structure is taken into account by using a porosity factor but for a grid resistance bulk porosity effects are presently ignored.

SEURBNUK calculations have been performed for tests WT13, WT15, WT18 and WT20 (see figure 1) to study the capabilities of the code in calculating fluid flow through permeable structures in several diverse situations. Tests WT13 and WT15 incorporate floor supported perforated diagrids as does WT20 which also incorporates a roof supported perforated dip-plate. A stacked array of spaced steel rods (allowing fluid flow) in test WT18 is used to model a neutron shield.

The values of the resistance coefficients used in the steady state pressure drop terms for the perforated plates and the stacked array of rods were derived from measured data (8). An epoch for each calculation is shown in figures 8 (a-d) to illustrate the flow pattern for the different situations. Generally the pressure drop across the resistance is associated with a reduction in fluid velocity, though in WT18 there is an increase in velocity within the neutron shield due to porosity effects.

The effectiveness of the SEURBNUK model in calculating the flow of fluid through a perforated plate is illustrated by considering test WT15 where the measured impulse levels on the upper surface of the diagrid and on the floor immediately below the diagrid are markedly different. The average value of the measured floor impulses are smaller by 40% compared to the average value on the diagrid. The calculated impulse variations derived from the pressure profiles are compared with measurement in figures 9(a,b) for a diagrid and floor position at the same radius. Figure 9b also shows the impulse variation on the floor for a calculation with the resistance coefficient set to zero and demonstrates that a substantial reduction in the calculated floor impulse is achieved (about 35%) with the introduction of the resistance. With the grid resistance modelled SEURBNUK is calculating the measured difference in impulse levels on the diagrid and floor well, (figure 9).

For the long vessel test WT20, which incorporates a roof suspended perforated dip-plate and deformable outer vessel, the measured roof impulses are reduced by a factor of about six compared with those measured for other long vessel tests (eg WT11, WT13). There is a well defined water impact on the outer portion of the roof but over the central region, above the dip-plate, the pressure profile is comparatively smooth and there is no well defined fluid impact.

With the dip-plate modelled by a fixed grid resistance SEURBNUK is able to reproduce the main features of this roof loading pattern. The presence of the dip-plate assembly reduces the velocity of the water surface over the central region to about 4 m/s compared to a velocity of about 20 m/s calculated for long vessel tests without dip-plates. Above the dip-plate SEURBNUK does not predict fluid impact on the roof and calculates the pressure as a smoothly varying cover gas pressure; the resulting impulse variation is in broad agreement with the measured value. On the roof outside the diagrid assembly where the water surface velocity is about 17 m/s a slug impact is predicted (figure 8d) although the detailed pressure pulses are not in accord with the measured profile.

The ability of SEURBNUK to model the radial flow through the rod array in WT18 is illustrated by comparing the dynamic pressure and impulse variations at positions on an inner rod, an outer rod and on the vessel wall (see figure 10). It is apparent that SEURBNUK is calculating the main features of the pressure profiles and is predicting the final impulses well.

In summary the results from these calculations are encouraging and demonstrate that the resistance option in SEURBNUK is a useful facility for modelling fluid flow through permeable structures. Future work on this topic will include a study of the adequacy of this steady state pressure drop treatment for modelling transient fluid flows through porous materials typical of COVA and reactor situations and the development of a perforated thin shell option in SEURBNUK.

6. PREDICTION OF ROOF LOADINGS

The loading of the reactor roof structure as a result of fluid impact is a topic of particular interest and the experimental arrangements in the COVA tests produce a variety of impact situations and roof pressure profiles against which to validate the codes. ASTARTE's ability in this area was discussed in the last review; almost invariably the standard ASTARTE calculations produce a series of pressure spikes bearing very little resemblance to the measured profiles. More recent work has included a study of the performance of SEURBNUK in predicting the roof pressure profiles and impulse levels.

In general the conclusions can be summarised by considering the short and long vessel COVA tests separately. In the short vessel tests the fluid crosses a gap of 25 mm before striking the roof and the impact surface generally has a domed shape. As illustrated in figures 11a to 11e, SEURBNUK is clearly distinguishing the characteristic shape and duration of the roof pressures though the absolute level of peak pressures is rather uncertain and to achieve an accuracy to better than about 50% further optimisation of the numerical parameters (eg time step) would be required. The predicted pressures are a marked improvement on previous ASTARTE predictions. Calculated impulses are in good agreement ($\pm$ 15%) with the measured values which range between 6.0 and 14 KPa.s, and though predicted roof pressures are $\sim$ 200 μs late this represents only a 20% error in the fluid transit time. Experiment WT9, however, is an exception. Here there is a larger error in the transit time and in the impulse during the initial impact; this may arise because of shortcomings in the modelling of flow around the top of the thick internal vessel.

This generally reassuring picture is not sustained for the long vessel tests which have a much larger, 85 mm, air gap above the fluid surface. For the bare rigid tank experiment WT5 the impact surface is essentially flat and the cover gas appears to play an important role. The SEURBNUK results are similar to the ASTARTE predictions reported earlier (4); the predicted impact time and pressure profiles are adequate, but significant detail in the measured pressure transients is not reproduced and calculated impulse levels are too high by about 45%, see figure 11f. Other long vessel tests incorporate internal structures (WT11, WT13 etc) and impulse levels are again too high, generally by about 30%. The duration of events on the roof is reasonably well predicted but otherwise the predicted pressures are not representative of the measured pressure records (figure 11g).

The cause of the significant overestimation of roof impulses in the long vessel tests is still being investigated.

7. CONCLUSIONS

In the last review (4) the strengths and weaknesses of ASTARTE were identified. ASTARTE would be most useful in the early stages of an excursion, particularly where detailed modelling of the core and the surroundings are required, being complementary to the SEURBNUK code which is more appropriate when significant fluid flows occur.

In reference 4 three main problem areas were identified and progress has been made in each case:-

Difficulties in reproducing the impulse in pressure waves reflected from the wall of the thick COVA vessels have been resolved by modelling, in the codes, the elastic response of the vessel.

A study of predicted roof loadings demonstrates that SEURBNUK produces much better estimates of roof pressures than ASTARTE for the short vessel COVA tests. This may occur simply because of the smoothing effect of numerical diffusion in the Eulerian code but in any case the predictions are probably adequate for current design requirements. The SEURBNUK roof pressures for most long vessel COVA tests however are not representative of the measured pressure profiles and predicted impulses are generally too high, by about 40%. Several possible reasons for these overestimates are being explored but the cause has not yet been identified.

Errors in the predictions of strains in thin vessels are common to both ASTARTE and SEURBNUK. Sensitivity calculations with variations in the vessel material data, based on the results from an extensive programme of recent material tests, indicate that material data uncertainties are unlikely to resolve these discrepancies. Attention is now turning towards the thin shell models and other theoretical aspects.

Considerable progress has been made in applying SEURBNUK to the more complex configurations of the later COVA tests which are more representative of reactor geometries. Recent additions to the code include a facility for modelling flow through permeable structures and calculations using this facility have been presented for a selection of COVA tests incorporating diagrids, dip-plates and neutron shields; in general the results are very encouraging.

In summary both ASTARTE and SEURBNUK have reached the stage where they provide a useful calculational capability for containment analysis within the confines of axisymmetric geometries. Recent and proposed developments of SEURBNUK will further enhance the codes' capabilities and continued validation of the codes against COVA experiments (and future planned tests) will further increase confidence in the codes' predictions.

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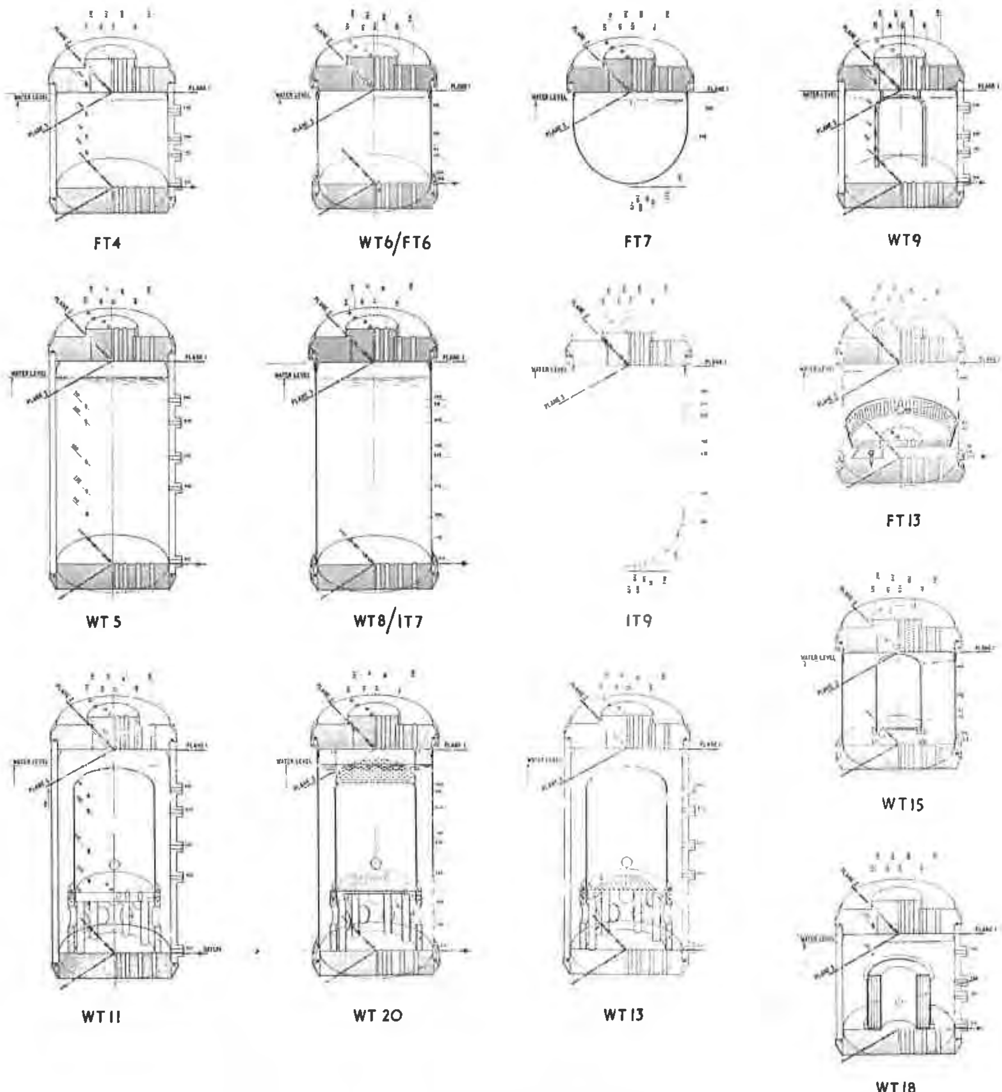

FIG. 1 THE EXPERIMENTAL ARRANGEMENTS.

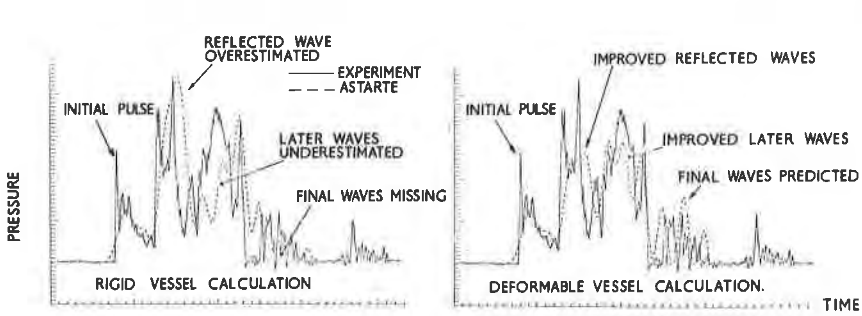

FIG. 2 PRESSURES CALCULATED BY ASTARTE FOR A FLOOR GAUGE IN WT5.

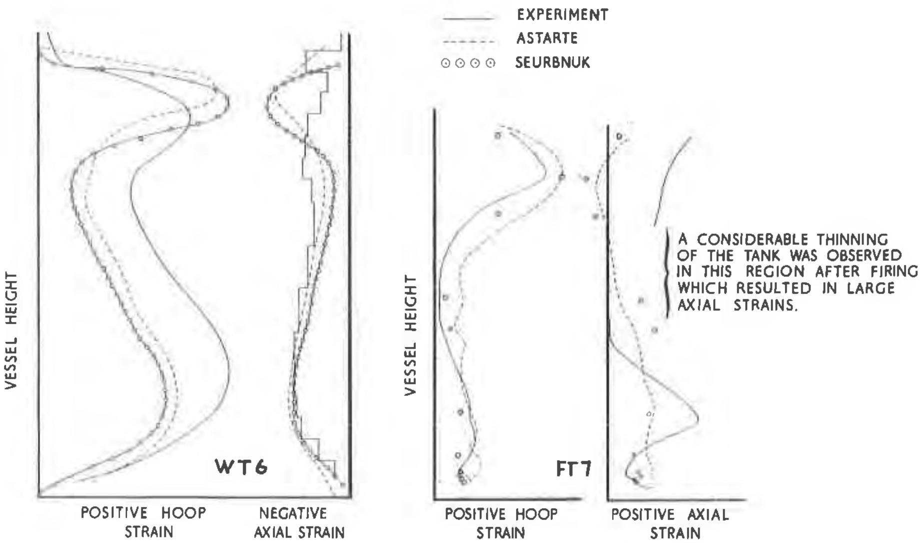

FIG. 3 COMPARISON OF MEASURED AND CALCULATED STRAIN PROFILES FOR WT 6 AND FT 7

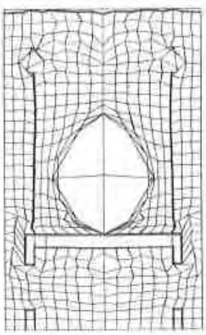

FIG. 4 EPOCH FROM AN ASTARTE CALCULATION FOR WT 11

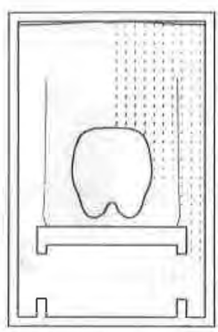

FIG. 5 EPOCH FROM A SEURBNUK CALCULATION FOR WT 11

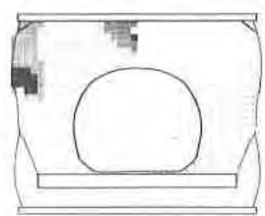

FIG. 7 EPOCH FROM A SEURBNUK CALCULATION FOR FT 13

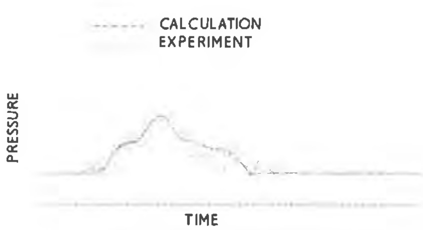

FIG. 6 PRESSURES CALCULATED BY SEURBNUK FOR A FLOOR GAUGE IN WT 11

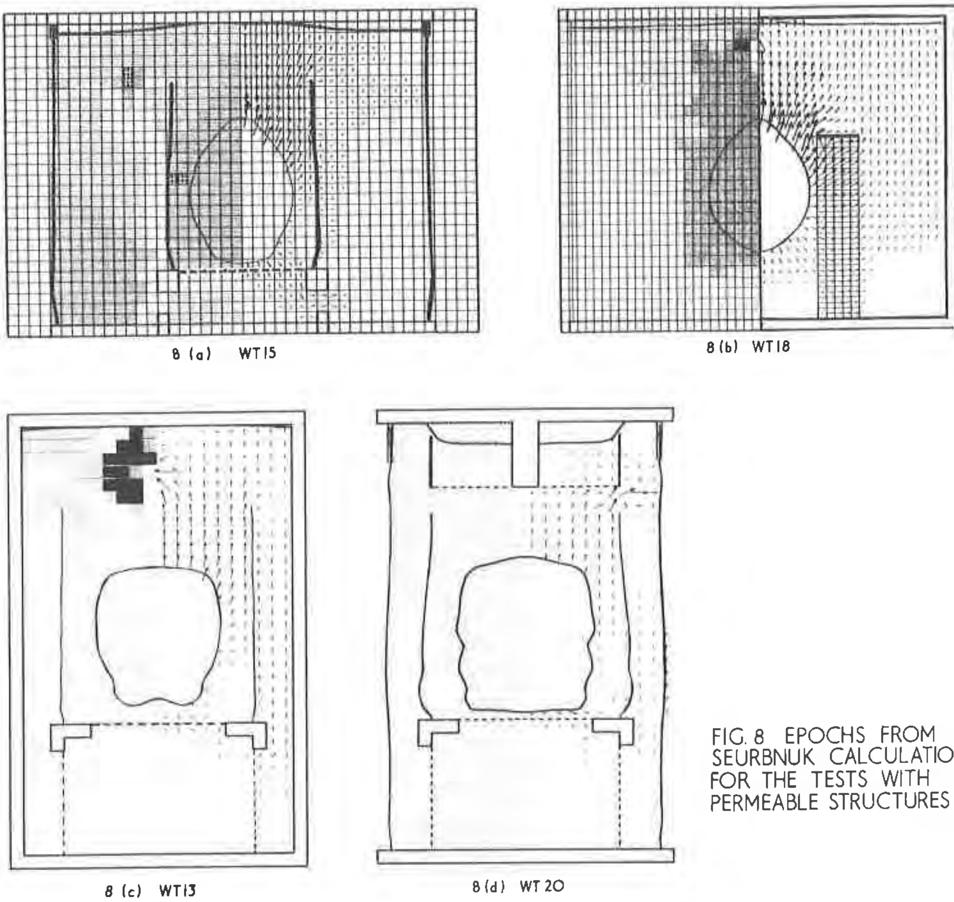

FIG. 8 EPOCHS FROM SEURBNUK CALCULATIONS FOR THE TESTS WITH PERMEABLE STRUCTURES

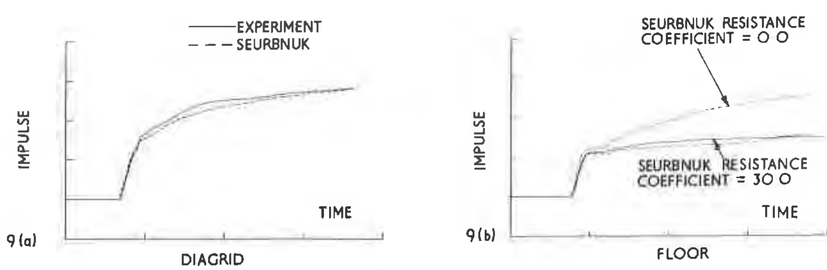

FIG 9 IMPULSES CALCULATED BY SEURBNUK FOR A DIAGRID AND FLOOR GAUGE IN WT 15

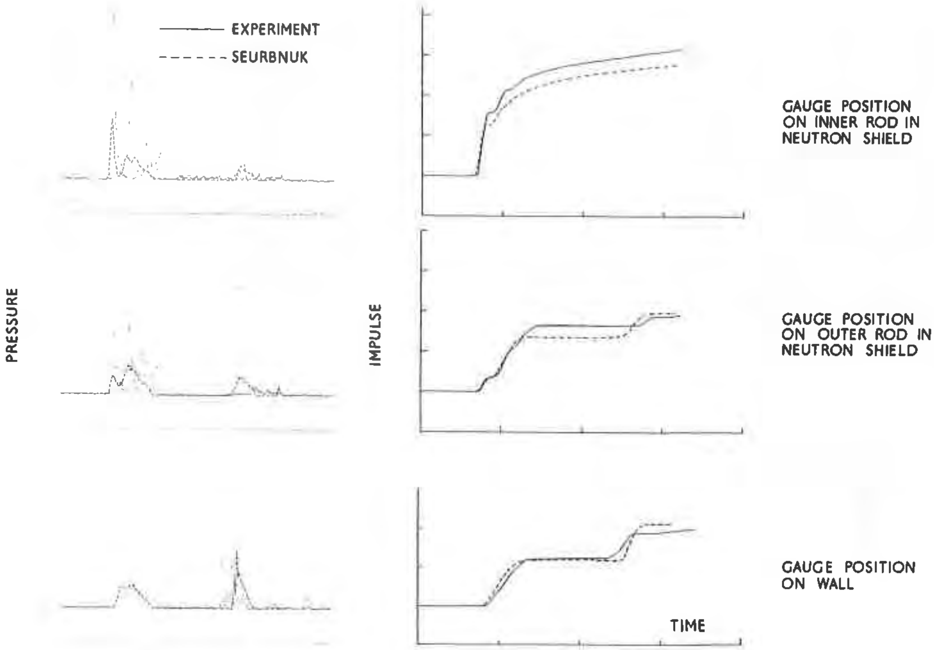

FIG. 10 PRESSURE AND IMPULSE CALCULATED BY SEURBNUK FOR WT 18

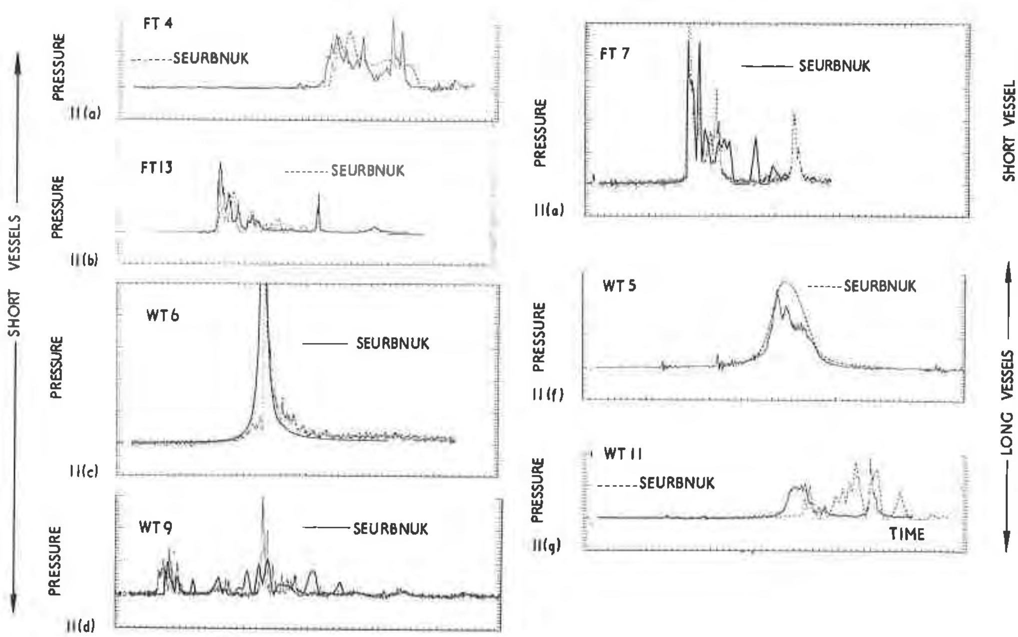

FIG. 11 ROOF PRESSURES CALCULATED BY SEURBNUK