Three-Dimensional Aspects of Fast Reactor Containment Loading Studies

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Theoretical assessment of HCDA loads on the primary containment of a fast reactor is performed with containment codes such as SEURBNUK which are restricted to 2-dimensional axisymmetric geometries. In a loop-type reactor the axisymmetric layout of the primary containment and major internal components conforms to an analysis of this kind. However, in a pool-type design the presence of intermediate heat exchangers and sodium pumps within the primary containment introduces a 3-dimensional aspect to the geometry that must be accounted for in CDFR safety studies. A series of "WINCON" experiments is being performed at AEE Winfrith to study this aspect of the containment loading.

In these WINCON experiments simple models of the containment geometry are subjected to an energy release provided by a low density explosive. Symmetric and asymmetric rings of roof supported cylinders were introduced to represent the IHX's and pumps. Data from the experiments indicate the effects of the IHX's/pumps on the containment loadings and the forces on the IHX's/pumps themselves.

Extensive instrumentation was used to measure the transient pressures on the containment vessel and the strains sustained by the vessel, also the pressures and loads on the cylinders and the fluid velocity between the cylinders.

The experimental results demonstrate that the ring of cylinders has a limited influence on the containment loadings and asymmetries are not marked even with one cylinder missing from the ring. Measured pressures on the cylinders and drag forces inferred from flowmeter measurements have been used as input to a simple model of the response of the cylinders; the analysis suggests that cylinder movement is sensitive to low level, long duration forces as well as to the main pressure loading.

SEURBNUK calculations have been performed for the experiments using a distributed resistance representation of the ring of cylinders. Comparisons of calculated and measured data illustrate that the axisymmetric code does reproduce most of the important events in this 3-dimensional configuration. A further calculation illustrates the relevance of the experiments to the reactor situation.

Future experiments will provide a more detailed study of the structural response of the IHX's/pumps and the need for a 3-dimensional containment code is discussed in this context.
1. INTRODUCTION

Theoretical assessment of HCDA loads on the primary containment of a fast reactor is performed with containment codes such as SEURBNUK[1] which are restricted to 2-dimensional axisymmetric geometries. It has been suggested[2] that the presence of intermediate heat exchangers and sodium pumps within the primary containment of a pool-type reactor such as the CDFR precludes the use of 2-D containment codes and that a realistic assessment of containment loads would require a coupled hydrodynamic and structural analysis in three dimensions.

An experimental programme is being performed at AEE Winfrith to study this aspect of the containment loading. A short series of experiments with simple models of the containment has been providing data on the loads likely to be experienced by the IHX's/pumps and the effect of these structures on the containment loadings. Data from this series are discussed in this paper and compared with SEURBNUK calculations. Future experiments will incorporate more representative modelling of the reactor configuration providing a detailed study of the structural response of the IHX's/pumps.

2. THE WINCON EXPERIMENTS

The WINfrith CONtainment experiments reported here were deliberately made simple, resembling previous COVA experiments[3]. Future experiments will incorporate the hemispherical geometry of the CDFR containment vessel. For the present tests, the basic experimental configuration consisted of a thin cylindrical outer vessel clamped to a massive floor and a massive roof. A thick inner vessel was incorporated to simulate the effect of the neutron shield (Figure 1). The vessel was partly filled with water, leaving an air gap above the water surface, and a spherical low density explosive (LDE) charge was used to represent the energy release from the excursion.

The first experiment, WINCON-01, provides a base line against which to compare the results of the next two experiments. In WINCON-02 a symmetric ring of roof-supported cylinders was introduced representing the IHX's and pumps. One of the cylinders was omitted in WINCON-03 simulating the gap required for the refuelling machine. The experiments were comprehensively instrumented.

3. THE SEURBNUK CALCULATIONS

SEURBNUK calculations were performed for the two axisymmetric experiments WINCON-01 and WINCON-02; the mesh layout for the WINCON-02 calculation is shown in Figure 2. Structures are assumed to be rigid except for the outer vessel which is modelled as a thin shell. The ring of roof suspended cylinders is modelled using an annular distributed resistance[4] with appropriate drag coefficients and porosity values assigned.
4. LOADS ON THE CONTAINMENT BOUNDARY

In the event of an HCDA the presence of the IHX's and pumps in the reactor will influence the loading on the containment boundary; a measure of this effect is provided by the experimental data on roof loading and vessel straining.

For the two tests with cylinders incorporated, about 65 quartz and tourmaline transducers were used to record transient pressures on the floor, roof, wall and inner vessel with the main emphasis on providing a good coverage of the radial and azimuthal variation of pressure across the roof. Approximately 20 strain gauges recorded the dynamic variation of hoop and longitudinal strain in the containment vessel; measurement of scribed lines on the vessel before and after firing and measurement by ρ-tape provided independent assessments of final strain. Similar measurements were made in WINCON-01.

Roof Loading

The geometrical containment presented by the ring of IHX's and pumps is expected to direct the coolant above the core barrel towards the roof and enhance the roof loading over the central plug region. The experiments confirm this hypothesis.

In the base line experiment WINCON-01 the pressure pulse resulting from the main fluid impact on the roof is followed by a moderate secondary pulse that propagates from the periphery of the roof following complete fluid impact. In WINCON-02 the containment provided by the complete ring of cylinders results in an earlier fluid impact on the roof and the initial pressure pulse is closely followed by a strong secondary pulse due to the reflection of the initial impact pressures from the ring of cylinders. The net effect on the total transient loadings on the central part of the roof is shown in Figure 3a; the peak forces for the two experiments are roughly equal though in WINCON-02 they act for approximately twice the duration. However, the integrated load in WINCON-02 at 3.5 ms when the major pressure loading is complete is only ~20% greater than in WINCON-01. By 10ms when the roof loading process is complete the difference rises to ~35%, Figure 3b.

In WINCON-03, roof pressures measured at equivalent positions near and far from the gap in the ring of cylinders exhibit only small variations and differences in impulse are not significant. However, though the azimuthal asymmetry is small, there is a noticeable effect on the total load on the central part of the roof; as expected, the load in WINCON-03 lies between the loads measured in WINCON-01 and WINCON-02 (Figure 3b).

SEUREBNUK calculations for WINCON-01 and WINCON-02 reproduce the important features of the roof pressure transients during the main fluid impact phase. The distributed resistance model for the ring of cylinders is able to model the confinement effect on the fluid slug and the reflection
of the fluid impact pressures towards the centre of the roof. Differences in the form of the total load transient on the central region of the roof, illustrated in Figure 3a, are adequately represented by SEURBNUK which predicts the impulse levels of about 800 Ns to within 20% and reproduces the comparatively modest increase in impulse when the cylinders are present, Figure 3b.

Vessel Strains

Changes in the loads on the containment vessel are reflected in changes in the vessel straining behaviour. Figure 4a shows the measured hoop strain profiles for each of the experiments; the corresponding longitudinal strains are small as a result of the clamped end conditions.

The bottom half of the containment vessel is protected by the presence of the strong inner vessel and consequently strains are small in this region and are little affected by the introduction of the ring of cylinders. In WINCON-01 significant straining occurs in the upper half of the vessel when the fluid is redirected outwards after impacting the roof. As expected the ring of cylinders in WINCON-02 affords some protection to the vessel and strains are reduced by approximately 20% from 4.5% to 3.5% absolute strain, but no azimuthal rippling of the vessel is observed. In WINCON-03 the absence of one cylinder increases the strains in the containment vessel over an arc+ 60° either side of the gap, the strains in this region approaching those experienced in WINCON-01 as illustrated in Figure 5. These typical strain data indicate that the degree of protection afforded to the containment vessel by the ring of IHX's/pumps is modest and that the induced asymmetry in the vessel strain pattern is not large.

Figure 4b shows the hoop strain profiles calculated by SEURBNUK for WINCON-01 and 02. The code consistently overestimates the strains by approximately 25% but the reduction of peak strain by ~20% with the introduction of the ring of cylinders is correctly calculated.

Discussion

An additional SEURBNUK calculation for WINCON-02 was performed with a UO₂ vapour expansion replacing the LDE charge, with an equivalent energy release down to 1 bar. The results illustrate that the same important phenomena occur for the two types of source apart from the initial shock loading exhibited by the LDE. Fluid impact on the roof occurs later with a UO₂ source and vessel strains are lower but the forms of the impact pressures and the strain profiles are similar, Figure 6. The similarity of these results for the two sources provides support for the extrapolation of the results of the study to the reactor situation.

5. LOADS ON THE IHX AND PUMP CYLINDERS

The IHX's form part of the primary containment boundary and it is important to be able to demonstrate their integrity in the event of an HCDA as their failure could lead to the release of fission products through the
secondary sodium circuitry. Furthermore the decay heat removal coils in the IHX’s should remain operable.

Pressures on the IHX/Pump cylinders

In WINCON-02, two nominally identical cylinders were machined to accept twelve pressure transducers providing comprehensive coverage of the axial and azimuthal variations of pressure (Figure 7a). In WINCON-03 one instrumented cylinder was positioned adjacent to, and the other diametrically opposite, the gap in the ring of cylinders.

The measured pressures indicate the main global hydrodynamic phenomena. Those on the sides of the cylinder and on the inward facing surface are qualitatively similar with the shock wave from the charge detonation and the pressures arising from fluid impact on the roof clearly identifiable. Pressures on the outward facing surface of the cylinders are markedly different being strongly influenced by the proximity of the deforming containment vessel. Figure 8a illustrates the form of the measured pressure transients on inward and outward facing surfaces and shows the pressure differential across the cylinder at a position close to the roof. Towards the bottom of the cylinder the pressures become less severe due to the protection afforded by the inner vessel. The asymmetry in WINCON-03 due to the gap in the ring of cylinders does not result in marked differences in pressure transients on cylinders near and far from the gap.

The distributed resistance model used in SEURBNUK cannot be expected to reproduce the detailed variations of pressure around the cylinders. Nevertheless the comparisons in Figure 8b demonstrate that the code does predict the main features of the measured pressure histories identified in Figure 8a though, as expected, the calculated initial shock wave is diffuse compared to measurement. Impulses (integrated pressures) on the cylinders are accurately calculated, the average overestimate on the inward facing surface being 12 ± 10% and on the back face 11 ± 4% at the end of the calculations.

Flows between cylinders

Newly developed drag-vane flowmeters, Figure 7b, were used to measure the variation of fluid flow between the cylinders: commercially available hot film anemometers proved to be insufficiently sensitive to changes of flow at high flow rates. Calibration of the drag vanes was performed in water flows produced by an adapted shock tube and, though still in the development stage, results from the drag vanes in the experiments are very encouraging.

Drag vanes were included in WINCON-02 and 03 installed directly into pressure transducer mountings approximately at mid-height on the instrumented cylinders, Figure 7a. One of the vanes used in WINCON-03 was mounted on a cylinder positioned next to the gap in the ring of cylinders. Peak outward fluid velocities of ~40m/s were measured subsequent to the impact on the roof, followed by a reversed flow reaching 20m/s after straining of the containment vessel terminated (Figure 9).
These measurements indicate that the fluid velocities between closely spaced cylinders in WINCON-02 and WINCON-03 are the same. Furthermore, the fluid velocity through the gap in the ring of cylinders in WINCON-03 is also similar, implying that the increased vessel straining in this region is associated with a large mass flow through the gap.

The distributed resistance model in SEURBNUK does not represent the detailed geometry of the ring of cylinders and therefore would not be able to resolve, for example, azimuthal variations in velocity through the gap. Nevertheless, the calculated fluid velocity transient is in good agreement with measurement; Figure 9.

Loads on the IHX/Pump support bolts

In experiments WINCON-02 and 03 one of the instrumented cylinders was bolted to the roof by means of three special hollow bolts. Strain gauges on the inside surface of these bolts were calibrated to provide a measure of the total load experienced by the cylinder; Figure 7a shows the orientation of the bolts. The periodic loads experienced by the bolts are shown in Figure 10. A lumped mass and spring model of the roof, cylinder and bolts has been used to assess the response of the cylinder to the measured pressures. This analysis has demonstrated that the motion of the cylinder is not a natural bending or rocking oscillation in response to the main pressure loading events alone, but that it is also sensitive to low level, long duration, forces. The analysis suggests that the cylinder is driven by a complex combination of applied pressures, drag forces due to fluid flow between the cylinders and cavitation in the fluid outside the cylinders - taking account of these features produces a satisfactory prediction of the cylinder motion (Figure 10).

6. FUTURE WORK

Future WINCON experiments will incorporate more detailed models of the IHX's and pumps and more representative modelling of the CDFR geometry. The experiments will use a thin hemispherically bottomed containment vessel and appropriate internal components. The IHX's and pumps will be modelled, together with shrouds and standpipes, in sufficient detail to provide a realistic assessment of the likely structural response and damage. For these future studies there is an incentive to develop an alternative energy source which is more representative of the postulated UO₂/sodium vapour expansion than the LDE source.

In parallel with this work, EIR Würenlingen are studying the possibility of improving the representation of IHX's and pumps and their support structures by introducing a thick moving porous structure model within SEURBNUK. A detailed assessment of the structural response of IHX's/ pumps and their supports will require three dimensional structural codes. Data from the planned WINCON experiments with more detailed models of the IHX's and pumps and more representative modelling of the CDFR geometry will
indicate whether there is also a need for three dimensional hydrocodes. A number of three dimensional hydrocodes do already exist including NEPTUNE and REXALE (ANL, Reference 2), PISCES 3DE (Physics International) and PHEONICS (CHAM Ltd) though PHEONICS does not model structural response aspects. The need for three dimensional codes arises if the response of components like the IHX's induce fluid structure interaction effects that are inherently three dimensional.

7. CONCLUSION
Measured data from three experiments (WINCON 01-03) indicate that asymmetries in the containment loading induced by symmetric or asymmetric rings of IHX's and pumps are small. SEURBNUK calculations have been performed for WINCON-01 and 02 with an axisymmetric distributed resistance model for the IHX's/pumps. These calculations provide a satisfactory estimate of the loads on the IHX's/pumps and the effect on the containment loadings. Future experiments will study IHX and pump response to HCDA loadings in more detail.

REFERENCES
FIGURE 1. THE EXPERIMENTAL ASSEMBLIES

FIGURE 2. THE CALCULATIONAL MESH LAYOUT

FIGURE 3. ROOF LOADINGS

FIGURE 4. HOOP STRAIN PROFILES
FIGURE 5. AZIMUTHAL VARIATION OF MEASURED HOOP STRAINS

FIGURE 6. SÜRBNUK RESULTS WITH A UO₂ VAPOUR EXPANSION COMPARED AGAINST A STANDARD CALCULATION WITH AN LDE CHARGE

FIGURE 7. (a) VIEW OF CYLINDER

FIGURE 7. (b) DRAG VANE FLOWMETER
Figure 8. Pressure Histories on a Cylinder

Figure 9. Fluid Velocities Between Cylinders

Figure 10. Loadings on Cylinder Bolts