EXPERIMENTAL AND ASSOCIATED THEORETICAL STUDIES
OF THE RESPONSE OF REACTOR STRUCTURES
TO HYPOTHETICAL CORE DISRUPTIVE ACCIDENT LOADINGS

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Data on hypothetical core disruptive accident (HCDA) loadings on both the primary containment and certain key components within it is essential both for design and safety assessment purposes. The simulation of such an event in a scale model and measurement of these loadings is often desirable. The practical difficulties associated with the representation of the loading phenomena do not outweigh the advantage of limited test programmes on complex geometries. Such experiments can be utilised both to supplement other hydrodynamic and coupled structural code development and verification activities, and to give data from which information for the full scale reactor system can be derived which is of immediate interest to designers and safety assessors.

A series of such tests has been carried out in the UK on nominally 1/20th scale models of the CDFR. The paper describes the third test in this series which was made on a geometry closely related to recent proposals for the UK CDFR design. The major components modelled as closely as possible included the primary tank, leak jacket, core structure, core support, strongback and above core structure. The roof, neutron shield and internal tank were simulated with structures which represented the essential mechanical features of these components. A number of these structures were instrumented with fast response transducers.

An important requirement in the simulation of an HCDA is an adequate representation of the nuclear excursion energy source by a chemical explosive. The charge used for this test was representative of an HCDA giving approximately 3 GJ work potential (at full reactor scale) when expanding against a 1 atm back pressure. The low density explosive used was manufactured from the materials used for the charges employed in the COVA series of code validation experiments, but was specially shaped and designed for this test series.

Results from the test are presented including load cell and pressure transducer measurements with derived impulses. Model structural records included both strain and displacement information.

To carry out a meaningful analysis of these experimental results, pre-shot static calibration tests were made on certain components to provide data for computation of stiffness and inertia values. The dynamic load transfer paths between both components internal to the primary containment and the containment itself have been investigated using this static calibration information in a 1D dynamic lumped parameter code MODSIM. The 2D hydrodynamic code SHURENUK has been employed both to check on experimental measurements of pressures within the primary containment - which form a part of the 1D MODSIM code input - and to provide directly roof impact loading predictions for comparison with the experimental data.
1. Introduction

This paper gives a description of an HCDA loading test on a detailed scale model of a UK CDFR.

Modelling and instrumentation features are discussed. Some test results and associated analysis are presented.

2. Objectives of Detailed Scale Model Tests

In the UK and at JRC Ispra a series of code validation (COVA) experiments\(^1\) designed to provide adequate data for the validation of a computational code oriented method of HCDA containment loading and response assessment is currently nearing completion. The timescale associated with this work necessitated a parallel approach to provide reactor designers with some directly measured test data for loadings on key components, and for this reason a limited programme of detailed scale model tests has been carried out. Such a programme enables approximate comparisons to be made between the loading and response characteristics of different designs and provides a certain amount of information which can be of use in COVA test sequence planning.

3. Model Design and Construction

For this test the linear scale factor was 1:24.5. The choice of scale was determined by the need to manufacture components to a high standard and the requirements of easy handling and assembly.

Mild steel was used for the manufacture of the leak jacket, primary vessel, strongback and diagrid. Water was adopted as a simulant for the sodium coolant.

The construction of the model is shown in Figure 1, each of the major components and the layout of the instrumentation is indicated. The main body of the model was suspended from the roof, and the roof was itself supported on three columns which were mounted on a large inertia block of 49 tonne weight. The roof consisted of a mild steel disc 1760 mm diameter and 50 mm thick, with a ring girder 200 mm wide and 300 mm deep forming the rim, and was designed to simulate the load deflection characteristic of the full scale structure. The support columns were clamped to the roof through this girder section.

Displacement and strain gauges monitored roof movement, and transducers were mounted in three radial lines in order to measure the fluid impact pressures. Load cells were used to measure the forces transmitted from major components to the roof.

Both the leak jacket and concentric primary vessel were hemispherically bottomed cylinders and were separately attached to the roof through arrays of 22 load cells. Strain gauges were mounted on the outside of both tanks and tourmaline pressure transducers were attached to the inside surfaces. Electron beam welding was specified for the construction of these vessels to minimise difficulties previously experienced with heat affected zones.
The rotating shield model was mounted on the roof with an arrangement of differential load cells that would respond to both upward and downward acting forces. The hold down bolts were made significantly overstrong to avoid failure and consequent loss of load measurement. The above core structure (ACS) was bolted to the shield and instrumented with both strain gauges and pressure transducers.

The core support system for the full scale reactor consisted of a short conical skirt with welded attachment to the primary vessel. It was desirable for a number of reasons not to simulate this form of attachment, therefore the model strongback was supported on a series of columns from the roof. The cross section of the model columns represented the scaled cross section of the reactor support skirt. Each of the 22 columns carried a load cell. The model strongback and diagrid were simplified representations of the full scale configurations having appropriate inertias and rigidities.

The charge occupied the core region. The breeder and fission gas plenum zones outside this region were modelled in some detail, but no simulation of the diagrid attachment restraint was provided. Tourmaline pressure transducers were mounted in four of the dummy breeder sub-assemblies, two on the inner ring and two on the outer ring. A section of each of these four sub-assemblies was removed in order to expose the measuring head of the transducer.

The neutron shield was mounted concentrically on the strongback with no restraints. It consisted of a thick walled cylinder sectioned into eight segments which were held together with thin steel cylinders inside and outside. This arrangement provided a simulation of the actual neutron shield by having a scaled mass and simulated low hoop strength.

The convoluted cylinder forming the multifoil tank of the reactor was modelled as a simple plain cylinder.

Both the neutron shield and multifoil tank were instrumented with strain gauges and pressure transducers. Each of the instrumentation sites are indicated in Figure 1.

4. Charge Design and Characterisation

One of the aims of this test was to ensure that the energy source simulated as closely as possible a fuel vapour explosion. An investigation by Cowler and Hoskin [2] indicated that a high explosive charge of low density would be satisfactory. Earlier work by Archibald [3] had shown that it was possible to vary the detonation velocity and pressure by varying the effective density of the explosive compound PETN, in a mixture with expanded polystyrene. This mixture was chosen for the low density explosive (LDE) used in this test series of CDFR models and the COVA programme [1]. Further reasons for the choice of this mixture were that its behaviour could be characterised by the procedure developed for more conventional explosives, so that its performance could be predicted independently, that it would be reproducible from test to test, and its behaviour would not be affected by the geometry of the surrounding model structures.
The prediction of the performance of this explosive required an accurate description of the pressure - volume - energy relation of the detonation products. To do this the JWL \( [4] \) equation of state was adopted as being the most suitable and determination of the parameters was carried out by Hoskin et al \([5]\). 

The charge used for the model test was a 200 g LDE containing 100 g of PETN. It was shaped to fit snugly into the model core region. The across flats dimension was 150 mm and the height 50 mm. Detonation was initiated at 30 points in the central plane of the charge by an exploding bridgewire system.

The equivalent full scale energy release of the charge on expansion of the detonation products down to a pressure of 0.1 MPa was 3.18 GJ.

5. Results of Test

5.1 Structural Damage

Apart from the disruption of the core, significant damage occurred in two areas. The above core structure collapsed and there were two fractures in the primary vessel, both at welded seams. The maximum permanent strain measured on the primary vessel was around 3%. The leak jacket suffered no damage or permanent straining. In addition the multi-foil tank was buckled and one of its welded seams fractured. The neutron shield showed permanent hoop strains of around 3% at the top and 8% at the base.

5.2 Dynamic Measurements

Only a representative selection of the many dynamic records obtained are included in this paper.

Figures 2, 3, 4 and 5 show the load time records obtained from a summation of the individual load cells associated with the rotating shield hold down, the primary vessel and strongback supports and the main support columns respectively. The similarity of the individual load cell measurements gave confidence in the actual measurements and indicated the symmetrical nature of the loading phenomena.

The early loads (up to 1 ms) in the rotating shield (Figure 2) bolts reflect forces transmitted directly through the AGS. The oscillatory loadings which follow arise from a number of different sources including motion induced by loadings in other areas and collapses of the AGS structure itself after about 5.5 ms. The primary vessel support load history (Figure 3) reflects the initial shock loading followed by a steady pressure build up beneath the core, the superimposed oscillatory pattern is consistent with the local system natural frequency. From Figure 4 the initial shock loading on the core support followed by a steady load build up as the region around the core becomes pressurized can be identified. Figure 5 shows clearly that the early loads on the model supports are downwards and are not exceeded by the subsequent roof impact forces.

A measurement of pressure taken at the bottom of the primary vessel with a tourmaline transducer is shown in Figure 6 and a pressure record typical of those obtained on the roof is shown in Figure 7.
6. Analysis of Test Results

The model loading and response was analyzed using both a one-dimensional lumped parameter code (MODSIM) and a two-dimensional hydrodynamics code (SEURENER).

6.1 The 1D MODSIM Code

The system representation used in this code is shown diagrammatically in a simplified form in Figure 8.

The vertical motions of the various model components, and the load transfers between them at model measurement stations were computed, using experimentally determined component deformation characteristics.

The LDE charge representation adopted was a uniform pressure bubble with a constant volume burn adiabat:

\[ p = 17039e^{-9v} + 1159.5e^{-2.4v} + 55.59v^{-1.1} \] (mPa)

where \( v \) = bubble volume ratio, where \( v = 1.0 \) initially

With 1D modelling a number of alternative assumptions concerning motion of the water above the charge are possible. Initial calculations assumed that bubble expansion produced acceleration of the ACS and water within the shield region.

Various assumptions have been made concerning the loads transmitted to the plug via the ACS from considerations of post shot deformation. Loadings on the plug region outside the ACS and on that area of the remainder of the roof which is impacted by the moving water in the model are computed using momentum conservation relations. The load on the primary tank was inferred from a combination of test observations and SEURENER predictions.

Analyses have shown qualitative agreement with observed component support load histories and indicated the reasons for the complex nature of the model rotating shield bolt loadings.

6.2 2D SEURENER Calculations

This code has been described in detail previously [6]. The geometry of the model was simplified somewhat to fit the code capabilities and the layout used is shown in Figure 9. Fixed rigid zone representations were employed for the roof, the upper part of the ACS and the outer strongback region. A 'thin shell' representation was used for the primary vessel, the neutron shield and the central region of the core support structure. In each case dimensions and densities were chosen to give correct stiffness and inertia.

Results for the early stages of the SEURENER calculation are shown on Figures 9 and 10. The former shows the pressure and flow field development at 1 ms, and the latter gives a comparison of pressure histories at selected locations.

7. Conclusions

This test has demonstrated that it is possible to obtain high quality records of model component load transfer as well as pressure and strain histories. It has also
shown that the loadings in rotating shield hold down systems are complex, particularly if system flow patterns are modified by structures above the core and emphasizes the need for experiments of this type.

Analysis of the results has shown that load transfer modelling is a necessary adjunct to complex hydrodynamics code evaluations of NGDA loading.

References


Figure 1 Instrumentation layout on model. Figure 2 Force on model rotating shield hold down.
Figure 3  Force on model primary vessel supports.

Figure 4  Force on model strongback supports.

Figure 5  Force on one of the model main support columns.

Figure 6  Pressure on the base of the model primary vessel.

Figure 7  Pressure on model roof at 200 mm radius.
Figure 8     Schematic for MODSIM Code.

Figure 9     SEURENUK model configuration.

Figure 10     Comparison of SEURENUK calculations with test data.