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# Sub-Assembly Cluster Explosive Tests and Analysis Related to Mechanical Consequences of Local Faults in LMFBRs

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## Abstract

The mechanical consequences to sub-assemblies (SAs) of a large LMFBR, if subject to energetic loading due to a local molten-fuel coolant interaction event, have been studied by tests at AWRE Foulness, using an explosive charge at the centre of small clusters of SAs. The SA wrapper (hexcan) material used in two tests was ductile and in one test embrittled by heat treatment (as a simulation of irradiation effects). The tests were instrumented with pressure transducers, strain gauges, load cells and accelerometers. Material property measurements and static crushing tests were also made to provide data for analysis of the cluster tests using finite element and lumped parameter methods. The tests have provided a valuable set of data against which such methods can be validated.

## 1. Introduction

The potential mechanical consequences to sub-assemblies (SAs) of a large LMFBR if subject to energetic loading resulting from a local molten fuel-coolant interaction event have been investigated with tests at AWRE, Foulness using an explosive charge at the centre of a cluster of SAs. Large clusters of simulated full-scale SAs were studied for both SNR300 and PFR type geometries some years ago. The SA wrapper (hexcan) material used for PFR tests was as manufactured steel at full ductility. Damage propagation was shown to be limited to two or three rows of SAs only but no theoretical analysis of the results has ever been attempted.

Proposals for more experimental work related to the CDFR design were made which would include effects of irradiated material properties. The ductilities (elongation to failure) of interest were 2 to 10% and could be produced by heat treating mild steel (rather than the expensive nimonic steel PE16 currently suggested for CDFR). The cluster tests were to be a centre wrapper (containing an explosive charge) surrounded by six test wrappers with good instrumentation. Associated crushing and material property tests were also to be done.

Considerable investigation of ways of producing controllable ductility properties in mild steel or PE16 was carried out. Unfortunately no reliable method was identified, but sufficient short (0.5m) lengths of wrapper with ductilities in the required range were obtained, to be able to mount one embrittled cluster test. A preliminary reference test with all fully ductile wrappers was also to be made. Sufficient data to provide validation for calculation methods under development was to be produced.

## 2. Description of Tests

The explosive charge used in all the tests described here was 1 kg of cordite. This would have a chemical energy of about 4.5 MJ but as used in the cluster tests is thought to result in a mechanical energy considerably less than this. The charge is placed in a gas generator, a steel cylinder with distributed holes, designed to give the desired pressure/time characteristic when in an overstrong SA. The pressure pulse has a rise time of about 1 ms to a peak value of about 40 MPa at wrapper mid-height and decays over a further 12 ms. The corresponding peak pressure in the gas generator was 100 MPa.

In the cluster tests the gas generator is placed in the simulated incident wrapper which is deliberately thinned at the corners from 2.6 mm to 0.5 mm to represent weakening by thermal stress or melting. The six test wrappers all 0.5 m long, 140 mm across flats are provided with simulant fuel pins (all mild steel except for some cable pins in the first test). These are held by 3 PE16 grids and grid legs over the wrapper length. The separation of the wrappers (6 mm as appropriate to the current restrained core design) is created by providing sachets containing silicon gel on all the faces.

Externally the wrappers were supported in the first test by 18 load cells (3 per face) held from the constraining cylinder by jacking screws. This cylinder (1 m diameter and 50 mm thick) was clamped to a base plate which was strongly bolted to a rigid plate in the concrete floor. The whole test was inside a 75 $m^3$ capacity tank which was filled with water to a depth of about 4 m. The second all ductile test and the third mixed embrittled test had more complete external support as shown in Figure 1. All tests were very thoroughly instrumented. In total 48 pressure transducers were used in the fluid, 48 strain gauges on steel walls, 18 load cells and for tests 2 and 3 only, 3 accelerometers. In the mixed embrittled test four of the test wrappers were heat treated mild steel, two of high ductility and two low. For the remaining places in the test two heat treated lengths of PE16 wrappers became available. The PE16 grids were also heat treated to a low ductility in this test.

The material properties of the materials used in the tests (necessary for subsequent analysis) were obtained once the explosive tests were complete. Laser-cut specimens were used in tensile tests, high strain rate tests and fracture toughness tests. Short lengths of the wrappers with internals were also used to obtain static force/deflection characteristics by crushing with both single sided and three sided support.

## 3. Results from Tests

Results from the three cluster tests are given in Table 1. All the instrumentation worked well and detailed records were obtained. In the first test the wrapper corner stresses exhibit a compressive phase; which indicates that the unsupported faces suffered buckling, making interpretation of the records difficult. This was the principal reason for the change to more complete support for tests 2 and 3. Damage to the wrappers in test is mainly symmetrical (see figure 2) - more typical of large cluster tests than was test 1. In test 3 all wrappers have cracks but these are only short in the case of the high ductility MS. The other types have one long crack and two or more short ones. The wrappers and their pin content kept their basic integrity after removal from the tests, although the grids (heat treated) had failed. It can be seen from table 1 that the peak gas generator pressure is similar to that in the overstrong wrapper test. However the peak pressure measured in the incident wrapper is limited to 10 MPa. Accelerometer records were obtained but when doubly integrated gave displacements which were not in good agreement with measured residual deflections.

The load deflection characteristic of a ductile SA was determined by a static crushingg test between two parallel flat surfaces. There was an initial steady increase in deflection associated with wall bending, followed by a rapid increase after hinge formation at the corners at a load of about 30 kN and a third steady increase phase after the pin/grid resistance comes into effect. Because, for cluster tests 2 and 3 particularly, it was thought that the test SA support was more akin to 3 sided rather than single sided, a cradle device was used for providing 3 sided support static crushing tests When used for . the ductile SA this produced much greater resistance with rapid increase in deflection only for loads above 160 kN. For the high ductility heat treated MS and the heat treated PE16 wrappers the collapse loads were 230 kN and 160 kN respectively.

The measured material properties of all the wrapper materials used in the cluster tests are listed in table 2. Full stress/strain characterstics were also obtained both in tensile conditions and at strain rates of about 10 per second. In the case of the heat treated materials used in test 3 the range of values is considerable according to the positions on the wrapper from which the samples were cut (eg for the nimonic steel the Ultimate Tensile Strength (UTS) value range was 414 to 517 MPa for the mean quoted). It can be seen from table 2 that the treatment of the mild steel used in test 3 did reduce its ductility from the normal value to an intermediate one (treatment 1) and to a very low value (treatment 2) while increasing the UTS by a factor of about 2. The heat treatment of the nimonic steel reduced its ductility (from 20%) but also decreased its UTS (from 540 MPa). At a strain rate of $10s^{-1}$ (estimated to be appropriate to the cluster test conditions) ductility is reduced by a further factor and UTS increased. There is a qualitative correspondence between the mean residual crushing results of table 1 and the mean UTS values of table 2, while the elongation to fracture is not so correlated.

## 4. Analysis of Tests

For the single-sided-support static crushing tests on ductile MS both static (ABAQUS code) and dynamic (EURDYN-01 code) finite-element plane-strain calculations were made. The ABAQUS calculation employed an 8 node isoparametric element and the EURDYN-01 a 4 node beam element. The measured elasto-plastic stress/strain material properties were used. No internal structure could be represented and since the effect of this was observed experimentally only for deflections over 18 mm, comparison is restricted to below this value. Agreement is good for EURDYN-01 (within 10% on load) and reasonable for ABAQUS (within 25%) although the latter calculation could only be made to a deflection of 11 mm.

For the three sided support static crushing tests the same two codes were used for ductile MS wrappers. Both sets of calculations agreed well with experiment (within 25%) up to deflections of 5 mm. The large increase in load required to reach plastic yielding with this form of support is confirmed. For the heat treated MS and PE16 wrappers only the ABAQUS code was used. Only limited comparison with experiment is possible because the cradle support tests produced buckling of unsupported faces and not readily interpretable characteristics. However agreement with the plastic load level is good.

The SPOKE code has been developed as a one-dimensional representation of an LMFBR core. Each SA is modelled as two point masses (representing front and back walls) connected by a spring corresponding to the crushing resistance of the SA. Resistance to bending along the SA length can also be represented. In the version which models the first cluster test, the back wall of the test SA and the load cell/jacking screw are treated as one mass with a stiff spring. Experimental data for the applied load from the incident, masses and spring force/deflection characteristics were used. No bending was represented. The calculated residual crushing for the tests is given in Table 1. Peak deflections were reached in 7 ms compared to peak strain time of 5 ms in test 1.

For the second and third tests the version of SPOKE used had the water filled gap between the back wall of the test SA and the load cell simulated by compressible fluid equations of motion in the gap plane. For the second (ductile MS) test all experimental data (including now the three-sided support static crushing characteristic) was used. Time to peak deflection now agrees with experiment. For the third test the crushing characteristic had to be taken from calculation (see above).

The experimental layout for test 2 (ductile MS) was modelled using EURDYN-IMP and 30° sector geometry. A half-side of the incident SA (including thinned corner), water gaps and test SA (one and half-half side) were included. Axial fluid motion can be represented by the use of super-elements. Results for pressure applied in test SA (peak of 10 and 20 MPa in 0.5 ms) and at mid-gaps (5 and 10 MPa in 0.5 MS) are given in table 3. Appropriate applied peak pressures to be used are uncertain because failure of the incident wrapper cannot be simulated. However the calculated fluid pressures, wall strains and deflections are in reasonable agreement with experiment. It was also observed that the fluid velocity in the gap between incident and test wrapper was essentially linear as assumed in the SPOKE code.

## 5. Discussion

The original cluster tests were of significance in showing that damage was limited to a few rows in large arrays. However they did not deal with severely embrittled materials or provide data for code validation and the more recent small cluster tests were designed to rectify this. The first ductile test, although the method of outer support used was considered unrepresentative, was still analysable. The SPOKE code calculations resulted in a residual deflection 35% greater on average than experiment. The second ductile test is considered to result in more realistic crushing and SPOKE calculations gave a residual deflection 10% less than the average of the test results (for 6 SA). The time sequence of events agreed well with experiment. For the third test using heat treated materials SPOKE calculations gave residual deflections in comparison to experiment only 20% greater for the higher ductility MS but much greater for the low ductility MS and PE16. Crack production was observed, especially for the low ductility materials. Residual deflections in test 3 are no greater than in test 2 and wrappers and pins kept their basic integrity even after removal from the test.

For test 3 materials full crushing characteristics were not available from tests and were provided by finite element code calculations of the type which compared well with ductile material crushing tests. However it would be preferable to use experimental data and this is now being produced using a suitable hydraulic loading rig.

It was noted that the experimental deflections correlate with the material UTS values but not with elongation values. An explanation for this and for the poor agreement of SPOKE with experiment when cracking is severe may require more than the principles involved in that code.

The SPOKE code has been applied to a reactor type situation for a line of full length SAs using test 2 type data plus a suitable bending characteristic. Qualitatively reasonable results (relative crushing deflections of successive rows of 1, 0.2, 0) were produced. Use could be made of the methods outlined in this note in safety arguments related to local fault mechanical consequences.

## 6. Acknowledgements

The skilful work of the Foulness experimental team, including particularly D Hood and R M E Goodman, is acknowlewdged. Thanks are also due to S Guiliani (JRC Ispra) for supplying a pre-release version of the EURDYN-IMP code, to A N Austin (Springfields Nuclear Power Development Laboratories) for the high strain rate measurements and to E A Little (Atomic Energy Research Establishment) for the fracture toughness measurements.

Table 1 Results of cluster tests and associated SPOKE calculations

| | | Test 1 | Test 2 | Test 3 |
|---|---|---|---|---|
| Gas generator peak pressure | (MPa) | 100 | 80 | 100 |
| Incident SA peak pressure | (MPa) | 10 | 10 | 8 |
| Peak load transmitted | (kN) | 100 | 150 | 150 |
| Pressures in front of wrappers | (MPa) | | 5-7 | 7-8 |
| Pressures in between wrappers | (MPa) | | 4-6 | 5-7 |
| Pressures at load cells | (MPa) | | 6-7 | 7-8 |
| Crushing across flats<br>(averaged over 140-370mm) | (mm) | 35 (MS pins)<br>37 (cable pins) | 17-24 | 16-19 (MS heat treated 1)<br>7-10 (MS heat treated 2)<br>20-24 (PE16) |
| Calculated from SPOKE<br>Crushing across flats (mm) | | 46 (MS pins)<br>50 (cable pins) | 19 | 21 (MS heat treated 1)<br>17 (MS heat treated 2)<br>35 (PE16) |

Table 2 Material Properties (mean values)

| Material | Ultimate Tensile Strength (MPa) | | Elongation to fracture (%) | | Fracture Toughness ($\text{MPa m}^{\frac{1}{2}}$) |
|---|---|---|---|---|---|
| | (a) | (b) | (a) | (b) | (c) |
| (1) Mild Steel (tests 1 and 2) | 440 | 530 | 27 | 12 | |
| (2) MS heat treated (1) (test 3) | 780 | 910 | 15 | 12 | 36 |
| (3) MS heat treated (2) (test 3) | 890 | 1080 | 3.1 | 2.2 | 28 |
| (4) Nimonic steel (PE16)(test 3) | 470 | 490 | 3.6 | 1.9 | 103 |

(a) Measured by AWRE Foulness

(b) " " SNL Springfields at strain rate $\sim 10s^{-1}$

(c) " " AERE Harwell

For materials (2), (3), (4) (test 3) the mean values for the wrapper with the smaller elongation of the pair are quoted.

Table 3 EURDYN-IMP calculation results for test 2

| Peak applied pressure (MPa) | 10 | 10 | 20 | 5 | 10 |
|---|---|---|---|---|---|
| Applied in incident SA or mid-gap | SA | SA | SA | gap | gap |
| No of super elements | 0 | 1 | 1 | 1 | 1 |
| Peak fluid pressure (MPa) | 3 | 3 | 12 | 5 | 11 |
| Peak fluid velocity ($Ms^{-1}$) | 24 | 26 | 53 | 27 | 73 |
| Strain % in incident SA (at 0.5 ms) | 18 | 20 | 75 | | |
| Strain % in test SA (peak) | 2.5 | 2.5 | 3.5 | 0.6 | 4 |
| Deflection of test SA (mm) | 6 | 6 | 12 | 4 | 12 |

Notes - incident SA with thinned corners, test SA normal MS

- applied pressure linear to peak at 0.5 ms

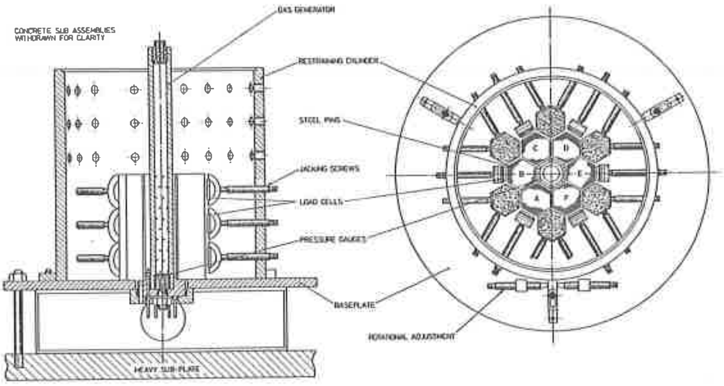

Figure 1 Schematic Drawing for Second Ductile Test

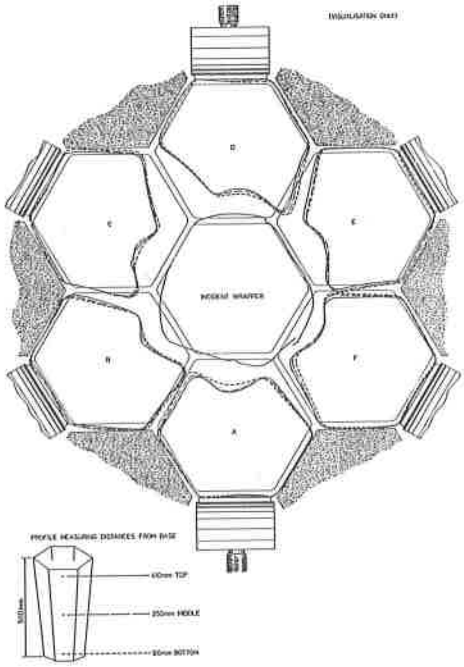

Figure 2 Residual Deformation of Wrappers Second Ductile Test

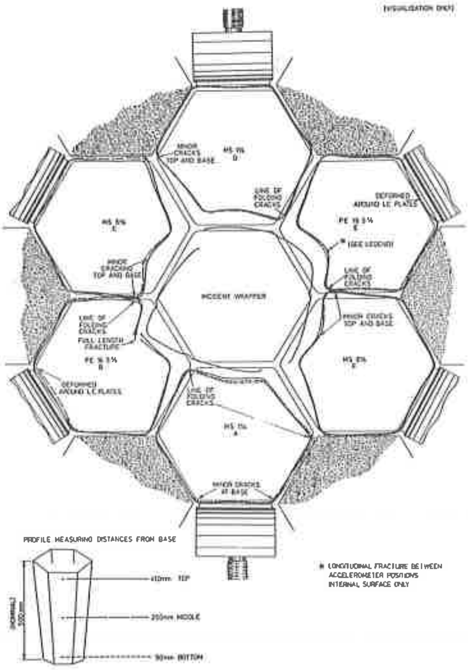

Figure 3 Residual Deformation of Wrappers Brittle Cluster Test