COUPLED HYDRODYNAMIC-STRUCTURAL ANALYSIS OF AN INTEGRAL FLOWING SODIUM TEST LOOP IN THE TREAT REACTOR

by

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Prepared for

5th SMIRT Conference

Berlin, Germany

August 13-17, 1979
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A hydrodynamic-structural response analysis of the Mark-IIICB loop was performed for the TREAT (Transient Reactor Test Facility) test AX-1. Test AX-1 is intended to provide information concerning the potential for a vapor explosion in an advanced-fueled LMFBR. The test will be conducted in TREAT with unirradiated uranium-carbide fuel pins in the Mark-IIICB integral flowing sodium loop. Our analysis addressed the ability of the experimental hardware to maintain its containment integrity during the reference accident postulated for the test.

Based on a thermal-hydraulics analysis and assumptions for fuel-coolant interaction in the test section, a pressure pulse of 144 MPa maximum pressure and pulse width of 1.32 ms has been calculated as the reference accident. The response of the test loop to the pressure transient was obtained with the ICEPEL and STRAW codes. Modelling of the test section was completed with STRAW and the remainder of the loop was modelled by ICEPEL.

The ICEPEL representation of the Mark-IIICB integral loop included two-dimensional, axisymmetric, hydrodynamic models for individual pipes and components coupled together to treat the structural response of the loop to the pressure transient originating in the test section. All pipes and components (excluding elbows) were modelled with deformable walls. A burst disc was included in the model at the lower bend of the loop with a rupture pressure threshold of 34.5 MPa. Analyses were performed to investigate the system behavior with and without the presence of this component.

The reference pressure pulse was applied at each end of the test section. Reduction of the system pressure due to the burst disc was clear. Results showed that rupture of the disc occurred at about 0.4 ms. At 1.0 ms the oppositely traveling pulses meet between the pump and burst disc and the peak pressure of 118 MPa is attained at this location. The input pressure pulse lasts approximately 1.5 ms after which the pressure in the system is relieved. No plastic deformations were observed in the ICEPEL analysis anywhere in the loop.

A stress analysis of the test section was accomplished with the STRAW code because it was best able to model the test train wall, a triangular duct surrounding the fuel pins. The model was constructed for a 60 degree symmetric section using quadrilateral continuum elements. This model was subjected to the reference pressure transient and underwent severe plastic deformation. The test train wall will deform enough to contact the cylindrical loop wall, but little plastic deformation is expected beyond this point of contact. These results along with the ICEPEL analysis of the system lead to the conclusion that the containment integrity of the Mark-IIICB loop will be maintained during the reference accident postulated for the AX-1 test.
There has been much interest in the LMFBR safety community concerning the potential for a large-scale sodium vapor explosion upon contact between molten fuel and liquid sodium in an LMFBR core. The advent of advanced fuel (carbide or nitride) core designs has prompted the development of experiments to investigate the phenomena associated with such rapid energy releases. Since carbide and nitride fuels have a higher thermal conductivity than the oxide fuels, conditions can be reached such that a vapor explosion may be possible, based on spontaneous nucleation theory. In the thermodynamic limit, up to half of the fuel energy could be transferred to work on the surrounding structures. Experiments of this sort provide an opportunity for applying analytical structural-response tools to predict the behavior of the experimental system under these extreme conditions.

This analysis addresses the hydrodynamic structural-response of the Mark-IIICB loop for TREAT (Transient Reactor Test Facility) test AX-1. Test AX-1 is intended to provide the foundation of a data base concerning the potential of a vapor explosion in an advanced-fueled LMFBR. The test will be conducted in TREAT with unirradiated uranium-carbide fuel pins in the Mark-IIICB integral flowing-sodium-loop shown in Fig. 1. Test AX-1 is the first carbide test to be done in TREAT in a flowing sodium environment. Fuel pin failure and expulsion of molten fuel into liquid-sodium-filled coolant channels are intended. A thermal interaction will take place among the molten fuel, fuel vapor, cladding fragments and droplets, and sodium. Sodium vapor, expanding around the failure site will impart kinetic energy to the surrounding liquid sodium coolant and drive it out of the failed region. Our analysis concerns the ability of the experimental hardware to maintain its containment integrity during the reference accident postulated for the test. Additional information on the experimental design, reference accident, and safety calculations are summarized in a report by Stephenson and Klickman [1].

In order to provide a thorough analysis of the system response to the accident transient, several hydrodynamic-structural codes were utilized in a complimentary manner, each treating a different aspect of the accident progression. Based on a thermal-hydraulics analysis and assumptions for fuel-coolant interaction in the test section, a maximum pressure pulse of 144 MPa and pulse width of 1.32 ms was calculated as the reference accident using REXCO-HT. A pulse such as this will set up a pressure wave propagating around the loop in both directions from the test section. Slug-impact consequences in the plenum region above the test section were evaluated using REXCO-HEP. The response of this test loop to the pressure transient was obtained with the ICEPEL and STRAW codes. Modeling of the test section was completed with STRAW, and the remainder of the loop was modeled by ICEPEL.

2. Source Pressure in the AX-1 Test Section

A reference accident has been postulated for the AX-1 test and the analysis of energy released in the transient was performed by Stephenson and Klickman [1]. The experiment itself will use a "double burst" transient produced by step insertions of reactivity at two points in time. This transient will initiate the melting of fuel and the failure of cladding as energy is released. A thermal-hydraulic calculation for the reference accident using the COBRA code yielded the fuel temperatures used as the driving function for the fuel-coolant interaction. Thermal expansion of the liquid sodium coolant in contact with molten fuel creates a pressure transient in the test section. These calculations were performed with REXCO-HT [2], modified to treat carbide fuel. Based on conservative assumptions of fuel
temperature, particle size, and mixing time (see Ref. 1), a pressure pulse of 144 MPa maximum pressure and pulse width of 1.37 ms was calculated. This source pressure history is presented in Fig. 2.

3. ICEPEL Analysis of the Mark-IICB Loop

The Mark-IICB loop, shown in Fig. 1, is the vehicle providing the containment for the AX-1 test. Sodium is circulated through the loop by means of a linear induction pump in the leg opposite the test section. Safety features in the loop include a burst disc at the lower bend to prevent system overpressure and a plenum region filled with inert gas above the test section to mitigate the effects of sodium expelled upward from the fuel region during a melt-down test.

3.1 ICEPEL Model Description

Figure 3 shows the ICEPEL [3] representation of the Mark-IICB integral loop. Two-dimensional, axisymmetric, hydrodynamic models for individual pipes and components were coupled together to treat the structural response of the loop to the pressure transient originating in the test section. All pipes and components (excluding elbows) were modeled with deformable walls. A burst disc was included in the model at the lower bend of the loop with a rupture pressure threshold of 34.5 MPa. Analyses were performed to investigate the system behavior with and without the presence of this component. The model ignores the test section of test AX-1 and assumes the input pressure pulse to be applied simultaneously at locations A and C. The approach is conservative, since it ignores the energy consumed in deforming the test section and thus overestimates the magnitude of pressure applied to the loop.

Junction B, in Fig. 3, models the return tee of the Mark-IICE loop. The gas plenum with initial volume of 970 cm$^3$ is modeled as a surge tank. The surge-tank model of the ICEPEL code considers the volume of liquid that enters or leaves as a change in the surge-tank gas volume. The corresponding surge-tank gas pressure is computed assuming an isentropic process for the argon gas. Thus, the surge-tank model reasonably accounts for the effects of the gas plenum on the pulse propagation through the system.

The pump is modeled as an annular-flow region by blocking the flow in the core of the pump using the rigid-zone-boundaries option of the generalized-piping-component model of the ICEPEL code. The blocked region of the pump is cross-hatched in Fig. 3. This model of the pump closely simulates the actual flow inside the linear-induction liquid-metal pump. However, the pressure head produced by the pump (~0.1 MPa) is considered unimportant in comparison to the magnitude of the input pressure pulse (~140 MPa) and was ignored in the analysis.

All pipes were divided into two radial zones, and the pump into four radial zones. All pipes were taken to be of Type 316 stainless steel and the pump of Inconel X-718. The system was assumed full of stagnant sodium (at 538°C) at the moment of application of the input pressure pulse.

3.2 ICEPEL Results

Figure 4 shows the pressure profiles along the pipe system at various times with the burst disc operational. For the pressure pulse traveling from location A toward the middle of the system, one can see the effects of the gas plenum (surge tank) at junction B as demonstrated in (a) reducing the pressure-peak magnitudes inside the pipe as the pulse approaches the return tee, and (b) further reduction in pressure-peak magnitudes as the pulse propagates around the return tee. The important result here is that the gas plenum caused a significant
reduction in the pressure-peak magnitudes of the pulses going into the return tee, and thus limited their severity.

At the entrance to the pump, the fluid goes through a series of changes in flow area, from that of the pipe to the increasing radial flow area in the inlet of the pump and finally to the annular-flow area of the pump. This sequence causes a net effect of a slight reduction in the pressure magnitudes as the pulse propagates along the pump. The result is seen to be a peak pressure of about 70 MPa at the pump outlet.

Meanwhile, the pressure pulse traveling from location C toward the middle of the system shows a large reduction in pressure due to the presence of the burst disc. The burst disc is calibrated to rupture at a pressure of 34.5 MPa (5000 psi). The results showed that it burst at about 0.4 ms, causing pressure-peak magnitudes of about 50 MPa to reach the middle of the loop.

Figure 4 shows that, at 1.0 ms, the oppositely traveling pulses meet between the pump and the burst disc, and the peak pressure of 118 MPa is attained at this location. After this time, the pressure waves travel back toward the test section. This process is further described in Fig. 5 with the pressure history at the point where the pulses meet. A pulse of 50 MPa from the direction of the pump encounters a pulse of 68 MPa from the lower bend and reinforce at this point for the maximum pressure. After 1.0 ms the residual pressure in this pipe is due to reflected waves. The input pressure pulse lasts about 1.5 ms, after which the pressures inside the system begin to show relief due to the two open ends of the system at locations A and C and to the gas plenum at B. No significant pressures remained in the system at 2.5 ms, the termination time of the analysis.

At 2.5 ms, the results showed that about 240 cm³ of sodium has entered the surge tank, causing the surge-tank pressure to rise to only 0.062 MPa (<0.62 atm). Although the sodium enters the surge tank at a velocity of 400 m/s, it has little influence on the containment integrity of the plenum region. A conservative scoping treatment of this region, using REXCO-HIP [4] with a rigid plenum cover and no internal gas pressure, revealed strains of the plenum wall to be less than 0.1%.

No plastic deformations were observed in the ICEPEL analysis anywhere in the loop. Hand calculations of the yield pressures of all pipes (Type 316 stainless steel at 538°C) and of the linear-induction liquid-metal pump (Inconel X-718 at 538°C) showed a yield pressure ranging between 201 and 235 MPa. The importance of the rupture disc in adding a safety margin to the loop was demonstrated by analyzing several cases without the rupture disc operating. Pressure levels and the resultant radial displacements of the loop walls were significantly reduced by the presence of the burst disc. However, even where the burst disc was not considered and the peak pressure rose to 215 MPa, the system remained elastic. Table I summarizes the maximum attained radial displacement of the walls of each pipe and of the pump for cases with and without the burst disc. The table also lists the yield value of each pipe and the pump and thus indicates no plastic deformation anywhere in the system.

4. STRAW Analysis of the AX-1 Test-Train Wall

A stress analysis of the test section was accomplished with the STRAW code [5] because it was best able to model the test-train wall, a triangular duct surrounding the fuel pins (see Fig. 1). This thick-walled structure is the basic component of the test train designed to resist short-duration pressure pulses, and to prevent against melting of the loop wall by molten fuel during the experiment.
4.1 STRAW Model Description

Figure 6 shows the STRAW representation of this section. It was decided that an independent model of the section would provide better accuracy, since the shape is not axisymmetric and much detail would be lost in approximating this section as cylindrical. The model was constructed for a 60° symmetric section of the test train, using 65 quadrilateral continuum elements. Five elements were used through the thickness of the duct wall. Continuum elements were used, since the triangular section is a thick-walled structure, having a "radius"-to-thickness ratio of approximately 3:1. This portion of the test section is fabricated from Type 304 stainless steel.

4.2 STRAW Results

The STRAW model was subjected to the reference pressure transient and underwent severe plastic deformation. The large pressure on the inner wall of the triangular duct created large stresses within the duct wall, producing significant shear and bending at the flat side. Figure 6 compares the section at 1.0 ms with the undeformed duct. At this time the triangular inner duct has been deformed approximately to the radius of the loop wall surrounding it. The maximum strains occur near the midpoint of the flat side, at the outer wall of the duct. Values of effective plastic strain of the duct, through the thickness at the flat, range from 3% at the inner surface to values in excess of the 22.5% ultimate strain at the outer surface.

Modeling the triangular duct separately in this manner provides a more detailed description of the structural response of the system to the pressure loading. The containment of the test section is not breached during the accident, even though the inner duct may be severely distorted. The ICEPEL results showed that pipes of similar dimensions behaved elastically during the pressure loading. This leads to the conclusion that the outer loop wall of the test section alone would be sufficient to contain the accident. The added thickness of the triangular inner duct provides an even greater assurance of containment integrity.

Results of the STRAW analysis are thought to be conservative. The radial deformation of the test-train wall may be overestimated because there is a possibility of sodium remaining between the test-train and loop walls, which would add resistance to radial motion. The test train may deform enough to contact the cylindrical loop wall, but little plastic deformation is expected beyond this point of contact, since the effective wall thickness would be increased and the pressure loading is nearly completed by this time.

5. Conclusions

The results cited lead to the conclusion that the containment integrity of the Mark-IICB loop will be maintained during the reference accident postulated for test AX-1. Conservative assumptions in the determination of the source term, regarding the efficiency of the fuel-coolant interaction, produces the maximum pressure pulse that may be reasonably anticipated. This pressure pulse was assumed to suffer no losses in the test section of the loop in the ICEPEL analysis. Although, with the burst disc operational, the results showed a marked decrease in the propagation of pressures through the system, no plastic deformation of the loop was encountered in calculations ignoring the presence of this component. Plastic deformation occurring in the test-train wall is due mainly to the shape of this component and does not compromise the integrity of the loop. These observations emphasize the margin of safety inherent in the Mark-IICB loop for the AX-1 reference accident.
Acknowledgment:

This work was performed in the Engineering Mechanics Section of the Reactor Analysis and Safety Division at Argonne National Laboratory, under the auspices of the U. S. Department of Energy.

References


## TABLE I. Maximum Attained Radial Displacement of Pipes and Pump for Cases with and without Burst Disc

<table>
<thead>
<tr>
<th>Approximate Yield Value of Radial Displacement, cm</th>
<th>Maximum Attained Radial Displacement, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Burst Disc</td>
</tr>
<tr>
<td>Pipe: A - B</td>
<td>0.00254</td>
</tr>
<tr>
<td>Pipe: B - Pump</td>
<td>0.00218</td>
</tr>
<tr>
<td>Pump</td>
<td>0.00634</td>
</tr>
<tr>
<td>Pipe: Pump - Lower Bend</td>
<td>0.00218</td>
</tr>
<tr>
<td>Pipe: Lower Bend - Burst Disc</td>
<td>0.00218</td>
</tr>
<tr>
<td>Pipe: Burst Disc - Lower Bend</td>
<td>0.00218</td>
</tr>
<tr>
<td>Pipe: Lower Bend - C</td>
<td>0.00182</td>
</tr>
</tbody>
</table>
Fig. 1. Mark-IICB Integral Loop Showing AX-1 Test Section.

Fig. 2. Source Pressure History for the AX-1 Reference Accident.

Fig. 3. ICEPEL Model of the Mark-IICB Loop.

Fig. 4. ICEPEL Pressure Profiles along the Mark-IICB Loop at Various Times.

Fig. 5. ICEPEL Pressure History at the Point where the Oppositely Travelling Pulses Meet.

Fig. 6. STRAW Model and Resultant Deformation of the AX-1 Test-train Wall.
PLENUM

• PUMP

• BURST DISC

LOOP WALL

TEST TRAIN WALL

25.4 R

ALL DIMENSIONS IN mm
ALL DIMENSIONS IN cm