The safety evaluation of reactor-components often involves the analysis of various types of fluid/structural components interacting in three-dimensional space. For example, in the design of a pool-type reactor several vital in-tank components such as the primary pumps and the intermediate heat exchangers are contained within the primary tank. Typically, these components are suspended from the deck structure and largely submersed in the sodium pool. Because of this positioning these components are vulnerable to structural damage due to pressure wave propagation in the tank during an HCDA. In order to assess the structural integrity of these components it is necessary to perform a dynamic analysis in three-dimensional space which accounts for the fluid-structure coupling.

In this study, we developed a model which has many of the salient features of the fluid-structural component system. We modeled the primary tank and the in-tank components as deformable elastoplastic structures, the sodium pool as an inviscid, compressible fluid, while the deck is taken to be rigid and fixed in space. The resulting transient response of this system due to an HCDA is presented.
The Liquid Metal Fast Breeder Reactors (LMFBRs) which have been developed to date were essentially designed either in a loop or pool-type configuration. With the loop type system, the reactor vessel contains only the reactor core, fuel handling equipment and instrument tree. The remaining components of the coolant system, such as the primary sodium pumps and intermediate heat exchangers (IHXs) are connected outside of the reactor vessel through the primary system piping. In contrast, the pool-type LMFBR has a relatively large diameter primary tank which contains all of the primary system components. These include the reactor core, core support structure, the instrument tree, fuel handling equipment as well as the primary pumps, intermediate heat exchangers and all primary piping.

A potential accident which must be taken into account in the structural safety assessment of LMFBRs is a disruptive accident (CDA). In the course of a CDA, the expanding core has several effects on the primary system structures. First, it creates pressure waves which propagate through the sodium pool and load the existing structures as well as the primary tank. In the case of a sodium slug which moves upward until it impacts against the top-side reflector, it is important that the consequences of a CDA must be included in the safety assessment of the primary system. This study would consist of a containment analysis of the primary core, a load impact analysis of the top-side closure and a component analysis of the primary system IHXs and primary sodium pumps. Because of the fundamental difference in configuration between the loop and pool LMFBRs each requires unique analysis. For example, in the loop design the IHXs are located outside of the reactor vessel and, therefore, they are not subject to direct loading from a CDA. The IHXs are, however, vulnerable to CDA generated pressure pulses that propagate through the primary system piping. In contrast, with the pool configuration the primary pumps and the intermediate heat exchangers are contained within the primary tank. These components are cantilever supported from the deck structure and are not subject to direct loading from a CDA. Because of this positioning they are vulnerable to structural damage during a core disruptive accident.

The concept of this paper is the dynamic structural response of an in-tank component (ITC), e.g., the primary sodium pump or IHX, of a pool LMFBR during a hypothetical core disruptive accident. Specifically the question of the ability of an ITC to resist the pressures generated in an energetic CDA is addressed. In order to assess the structural integrity of these components it is necessary to perform a dynamic analysis in three-dimensional space which accounts for the fluid-structure coupling.

Reference for description

The reference reactor used in this investigation was developed as part of a study [1] conducted at Argonne National Laboratory (ANL). The design was of an 1200 MWe (e) pool-type system which was based on the cold-pool (FBR-16) design. The main components of the system are shown in Fig. 1 which is a schematic elevation view of the reactor. These components are the reactor core, core support structure, intermediate heat exchangers (IHXs), primary pumps, primary and secondary tanks and the shield-deck structure. The instrument tree and fuel handling machinery are not shown. From the plan view (Fig. 2) it is seen that the primary tank contains three primary pumps, six IHXs and two storage baskets. The diameter and height of the primary tank are 21.4 m and 20.9 m, respectively. The primary tank would be constructed of austenitic stainless steel (Type 304 or 316).
The in-tank components, that is the primary pumps and IHXs, are antisymmetrically supported by the deck structure. Figure 3 shows the design used to support the primary pump assembly. The pump assembly is supported by the shield deck which is, in general, a concrete-filled, plate composite structure. The pump assembly consists of a motor which is located above the pump support and the impeller which is positioned at the bottom of the assembly in the sodium pool. The motor is connected to the impeller by a drive shaft and flexible couplings. A pump casing is used to enclose the above assembly. In order to minimize structural exposure to the pump, Figure 3 shows that a separate protective annular shroud was designed to surround the equipment. Therefore, during a CDA the shroud would provide a structural barrier between the pressure waves which are propagating through the sodium pool and the primary pump. Though it is not discussed here a similar protective shroud is used in the design of the IHX.

3. Analytical Model

For a preliminary study of this complex problem, we developed a simple model with many of the salient features of this fluid-structural component system. To begin, we modeled the primary tank and the in-tank component as deformable elastohydraulic structures. 304 SS, the sodium pool as an inviscid, compressible fluid, while the core is taken as rigid and fixed in space. The effects of slug impact are not addressed. Subsequent analysis will include both a deformable deck and slug impact effects.

A reasonable model can be developed by assuming a 12° repeated symmetry of the array. A model (Fig. 4) which includes a 12° sector of the sodium pool, one-half of an in-tank component (primary pump or intermediate heat exchanger) and a 12° sector of the primary tank is sufficient. Because of these symmetries we can define the symmetry planes labeled in Fig. 4. Symmetry plane S1 is the plane OACEO which originates along the tank axial centerline of the tank and passes through the axial centerline of the in-tank component. The symmetry plane S2, OBDEO also originates along the tank axial centerline, but it passes halfway between the in-tank components. The symmetry plane S3 ECDE is a horizontal plane.

The finite-element mesh for our model is shown in Fig. 5. The entire mesh consists of 80 triangular plate/shell elements and 127 hydrodynamic elements. Our model for the in-tank component consists of 38 triangular plate elements, which simulates the entire 12° but only one-half of the circumference of an in-tank component. The boundary conditions at the top are zero displacements and rotations. The nodes which lie in the symmetry plane S1 are restricted to motion only in that plane. The remaining nodes of the component model are free to move arbitrarily in three-dimensional space.

The model for the primary tank consists of 42 plate elements. The boundary conditions at the top of the tank are zero displacement and rotations which simulate the attachment of the tank to the rigid deck. In contrast, the boundary conditions at the bottom of the tank model are such that these nodes are allowed to translate in the symmetry plane S3. Rotations which preserve the symmetry are allowed. This boundary condition arises from 12 antisymmetrical studies which show that the motion of the sodium is essentially horizontal at this elevation (approximately mid-core height).

Nodes which are connected entirely by fluid elements are free to move arbitrarily in three-dimensional space, with the exception of those which are restricted to motion in a symmetry plane. Figure 6 is a plan view of our model.

The expanding core gas bubble is modelled as a pressure cavity which exerts a pressure on the bubble-sodium interface. A pressure-volume curve representing an adiabatic expansion
The above finite-element model was analyzed with an ANL developed code named NEPTUNE [2]. The structural components of the model are represented with triangular plate elements and the fluid is represented by an Lagrangian hexahedral hydrodynamic element. The plate/shell element [3] is formulated in a local corotational coordinate system which leads to simple relations for the nodal variables. Local to global vector transformations are used to convert local nodal forces into global nodal forces for use in the semidiscretized equations of motion. The constitutive algorithm which is used with the element can model elastoplastic material behavior. It uses a subincrementation procedure with a yield return scheme to increase the accuracy of integration of the constitutive equations. Because of the above formulation the element is capable of treating large displacement/rotation problems. The Lagrangian hexahedral hydrodynamic element is formulated using rate-type stress-strain relations in conjunction with a rate- deformation tensor. Thus, this element is applicable to large deformation problems. The semi-discretized equation of motion are integrated in time with the explicit form of Newmark's [4] integrator.

4. Results and Conclusions

Using the above model and analytical tool the following results were obtained for the dynamic response of the system. Once the basic overall dimensions of the system are established and the loading source defined, the dynamic response will be influenced by the wall thickness of both the primary tank and the in-tank component. A scoping study was performed in which wall thicknesses were varied and the resulting displacement and stress histories for both the in-tank component and primary tank obtained. Reasonable values for wall thicknesses are 2.54 and 3.05 cm for the primary tank and 1.27 and 2.54 cm for the shroud of an ITC.

For the case of a 3.05 cm thick tank wall and a 1.27 cm thick shroud wall, Fig. 7 shows the radial displacement histories for the bottom of the ITC and the primary tank at the same elevation, that is points C and P in Fig. 4. The maximum displacement of the component is 30.7 cm and occurs 50 ms after the initiation of cavity pressurization while the tank's maximum displacement is 26.2 cm at 0.67 ms. The clearance between the ITC and the tank is reduced from its initial value of 99 cm to 94 cm during this motion. Table 1 lists the peak displacements and the times at which they occur for several combinations of ITC and tank wall thicknesses.

This preliminary study showed that the dynamic response of an in-tank component is such that the peak displacement of the component is sufficiently small so that contact between the component and the tank is not anticipated. The calculations also indicate that the peak stresses are well below the ultimate stress values.

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References


Table I. Peak Radial Displacements

<table>
<thead>
<tr>
<th>Primary Tank</th>
<th>In-tank Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>h (cm)</td>
<td>d (cm)</td>
</tr>
<tr>
<td>2.54</td>
<td>26.2</td>
</tr>
<tr>
<td>5.08</td>
<td>14.6</td>
</tr>
<tr>
<td>5.08</td>
<td>14.3</td>
</tr>
<tr>
<td>h = wall thickness</td>
<td></td>
</tr>
<tr>
<td>d = radial displacement</td>
<td></td>
</tr>
<tr>
<td>t = time</td>
<td></td>
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</table>
Fig. 1. Schematic Elevation of the Reference Pool-Type LMFBR.

Fig. 2. Schematic Plan View of the Reference Pool-Type LMFBR.

Fig. 3. Primary Pump Configuration.

Fig. 4. Sector Model of Primary Tank, Dock, Sodium Pool and In-Tank Component.

Fig. 5. Finite-Element Mesh of the Sector Model.

Fig. 6. Top View of Finite-Element Mesh.

Fig. 7. Radial Displacement Histories for the ITC and Primary Tank (Points C and P of Fig. 4).
LEGEND

- = Component, 1.27 cm

= Tank, 5.08 cm