FLUID-STRUCTURE INTERACTION ANALYSIS OF A DECK STRUCTURE DURING A HCDA

R. F. KULAK

Reactor Analysis and Safety Division, Argonne National Laboratory,
9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.

Summary

Presented here is an assessment of the structural integrity of the deck structure of a pool-type LMFBR during a Hypothetical Core Disruptive Accident (HCDA). During this accident the sodium above the core is propelled upward until it impacts against the deck structure. This hydrodynamic loading could produce (1) significant structural damage and (2) sodium leak paths.

The deck is a three-dimensional composite structure of beams, plates and concrete fill. It is supported at its outer periphery by steel columns embedded in the surrounding concrete, radial biological-shield. The deck provides top closure for the main tank and support for the intermediate heat exchangers, primary pumps, rotating plugs, and primary and secondary tanks. A finite-element model is used to study the deck dynamics during slug impact. By using the symmetry of the system, a sector model which accounts for the salient features of the system is developed. The main radial I-beam, component support I-beam and bottom annular plate are modeled using triangular plate elements. The concrete fill is modeled using hexahedral continuum elements.

Using the above finite-element model the dynamics of the deck during a HCDA are investigated. The structural stiffening effect of the concrete fill on displacement response is studied by comparing results obtained from two cases. The first case accounts for both the mass and structural effects of concrete and the second only accounts for the mass effect. Results are presented for deck displacement and velocity histories and deck support column reaction forces.

1. Introduction

The safety evaluation of a 1200 MW(e) pool-type Liquid Metal Fast Breeder Reactor deck structure during a hypothetical core disruptive accident (HCDA) is addressed. The pool-type LMFBR is designed with the entire primary cooling system contained within the main tank which is filled with a pool of liquid sodium. This includes the following components: reactor core, core support structure, instrument tree (upper internals), primary pumps, intermediate heat exchanger (IHXs), all primary piping and the in-vessel handling equipment. The top of the tank is covered with a deck structure which also supports some of the components.

One of the main safety questions which has been raised in connection with the pool design concept is the ability of the primary system to withstand the effects of a significant core disruptive accident (CDA). The analysis of reactor containment can be subdivided into the assessment of the structural integrity of two main components: the primary tank and the deck structure. Under ordinary operating conditions the main function of the tank is to contain the liquid sodium which is at a temperature of about 382°C and weighs about 44 MN. In addition, the tank also provides support for the reactor core and core support structure. With the pool-type configuration there are no penetrations in the tank below the liquid sodium level.

Topside containment is provided by a deck structure. Under normal conditions the deck provides support to the equipment which penetrates into the sodium and to the rotating plugs. The deck is a composite structure of beams, plates and concrete fill. Steel columns embedded in the surrounding concrete, radial biological-shield provide support for the deck at its outer periphery.

During a core disruptive accident (CDA) the expanding core (1) generates pressure waves which travel through the sodium pool and load the primary tank and (2) creates a sodium slug which travels upward until it impacts against the deck structure. This hydrodynamic loading of the deck could produce (1) structural failure and (2) sodium leak paths. If the structural damage is significant, the deck would not be capable of performing its equipment support function. A breach in topside containment would permit a substantial inventory of sodium to enter into the secondary containment. The resulting pressure increase within the containment building due to a sodium-oxygen reaction could produce structural damage to the secondary containment. In view of the above a structural analysis of the deck under the transient conditions of a CDA is necessary in the safety analysis of LMFBRs.

An initial study on the dynamic response of a large pool-type deck structure to a HCDA was reported by Kulak [1]. There, a sector model was developed which treated the beams and plates of the deck structure as structural members but neglected the structural effect of the concrete fill. In this study, the structural effect of the concrete fill is taken into account.

In the following sections, the deck configuration which is here analyzed is described. This is followed by a description of the deck model and the associated finite-element discretization. A brief description of the computer code used is then presented and finally the results are discussed.

2. Deck Structure Description

The reference deck selected for this analysis was developed as part of a study [2] conducted at Argonne National Laboratory (ANL). The reference reactor is shown in Fig. 1 and it is of commercial size, that is about 1200 MW(e). The deck is designed as a composite structure of steel and concrete. The main structural elements of the deck are a series of radial I-beam which are supported at their outer radius by steel columns embedded in the surrounding concrete. At their inner radius these beams are welded to an inner ring which provides support to the rotating plugs. The deck also provides support to the primary pumps and intermediate heat exchangers which penetrate through the deck into the sodium pool. These components are supported between two main radial beams by vertical nozzels welded to a component support beam. The component support beam is welded at its inner and outer radii to the inner and outer rings, respectively. The deck is filled with concrete to half its depth. The concrete serves two purposes. First, it provides ample radiation shielding to the environment and second it adds stiffness to the deck.

The deck covers a main tank which has a diameter of 21 m. The diameter of the rotating plug assembly is about 9 m. The heights of the radial I-beams and the component support beams are 3 m and 1.5 m, respectively. The beams, plates, nozzles and rings are constructed from Type T1 steel which is suited for impact type loading.

3. Finite Element Analysis

In the initial study of this problem, a model was developed which treated the beams and plates of the deck as structural members but neglected the structural effect of the concrete fill. The concrete fill, In-tank Component and rotating plugs were considered to be concentrated masses at their appropriate locations. The recent development of a three-dimensional continuum element provides the necessary capability to treat the structural effect of the deck's concrete fill. This study presents some preliminary results on dynamic deck response which includes the structural effect of concrete.

As in the previous study, a sector model of the deck was developed based upon the repeated symmetry of the system. This model (Fig. 2) accounts for the radial I-beam, component support beam, In-tank Component nozzle, annular plate, inner and outer rings and the concrete fill. The In-tank Component and the triple rotating plugs are treated as concentrated masses. The finite element mesh for this model is shown in Figs. 3 to 6 and it is subdivided into smaller elements than the previous mesh. Fig. 3 shows the discretization of the entire model while Figs. 4 to 6 illustrate the discretization of the various deck components. The material properties used for the various structural members are listed in Table 1. The steel was assumed to follow a bilinear, universal stress-strain curve based upon the mechanical properties listed in Table 1. The material properties of the concrete biological shielding are also shown in Table 1.

During a HCDA the sodium slug impacts against the deck structure and a fluid-structure interaction follows. This impact in effect produces a pressure loading on the underside of the deck. In the initial study, a decoupled analysis was performed in which the deck pressure loading (Fig. 7) was obtained from a two-dimensional axisymmetric containment code REXCO-HEP [3]. This was based on a core with an average temperature of 4800°K at the time of disruption. The total energy available in expanding the core to the final, quasiequilibrium pressure of the containment vessel is about 1400 MW-sec. The total energy available at one bar would be about 2720 MW-sec.

Two models are used to determine the stiffening effect of the concrete fill. The first model is as described above, that is, the structural effect of the concrete fill was taken into account. The second model is identical to the first with the exception that only the mass effect of the concrete is considered. This was done by distributing the mass of the concrete along the radial and component beams, the inner and outer rings and the component nozzle.

Both models treat the mass of the rotating plug and the component as concentrated masses located at their attachments to the deck. These models are both subjected to the pressure time history shown in Fig. 7. The total loading applied to the models consists of the pressure applied to the deck's underside and a line load acting on the inner ring to simulate the pressure loading acting on the plug.

The dynamic response of the above models was obtained with the NEPTUNE code [4]. The code was developed at ANL to treat the nonlinear elastoplastic three-dimensional fluid-structure interactions of fast reactor components. From the above models it is seen that there are basically two types of structural components which must be represented: steel plates and concrete fill. A triangular plate element, which was originally developed for the SADCAT code [5] is used to model the beams, rings, nozzle and bottom plate. The plate element is formulated using a corotational coordinate system which enables the use of simple strain-nodal displacement and stress-nodal force relations. This plate element can be subjected to linear in-plane and cubic transverse displacements. The orientation of lumped masses is described by unit vectors so that arbitrarily large rotations can be treated. The material response is taken to be elastoplastic. The integration of the elastoplastic constitutive equation employs a subincrementation procedure and a yield surface return scheme so that the end-of-step stress lies on the yield surface. The concrete fill is modelled with hexahedral continuum elements. Within each element trilinear isoparametric interpolating functions are used to describe the unknown kinematic fields. Because a rate-type constitutive relation is used in conjunction with a rate-of-deformation tensor, the formulation is applicable to large deformation problems. The discretized equations of motion are directly integrated in time using the explicit form of Newmark's [6] method.

4. Results

The computed response of the two models resulting from the pressure loading (Fig. 7) is presented in Fig. 8 to 10. The vertical displacement of the radial I-beam at its connection to the inner ring (point A in Fig. 2), is shown in Fig. 8 for the cases with and without the structural effect of concrete. It is seen that the structural effect of the concrete fill was to reduce, by 31 percent, the peak displacement of the deck from 5.2 cm down to 3.6 cm. The peak displacements occurred at 30.8 ms for the model which neglected the structural effect of concrete and at 21 ms for the model which included the structural strength.

The velocities of the inner ring and the mid-point of the nozzle, that is points A and B, respectively, of Fig. 2, are shown in Fig. 9 for the case which does not include the structural stiffness of concrete. It is seen that a peak velocity of 390 cm/s occurs at 9.8 ms for the inner ring and a peak of 222 cm/s at 14 ms for the component nozzle.

The final set of results presented are the vertical reaction forces (Fig. 10) of the columns which support the main radial beams. The peak force when the structural effect of concrete is taken into account is about 172 KN and it occurs at about 20 ms after the initiation of deck loading.

5. Concluding Remarks

Finite element models are developed to represent the deck structure of a reference large LMFBR. The resulting fluid-structure interaction between the deck and sodium slug during a HCDA is treated by decoupling the problem. The slug pressure history on the deck is obtained from a two-dimensional containment code calculation. The finite element models are loaded with this pressure history and the resulting dynamic response obtained. The effect of treating the structural stiffness of the concrete fill on the dynamic response of the deck is studied. The vertical reaction forces of the supporing columns is also studied. The results of the above studies present useful data for use by reactor engineers when designing deck structures to maintain structural integrity during CDAs.

The above models represent an intermediate stage in the model development for this problem. A model which is currently under development treats the rotating plug assembly and the in-tank component with rigid-body elements which are attached to the flexible deck structure. The sodium pool is modeled with hexahedral hydrodynamic elements that interact with both the rigid-body elements and the plate elements. A slug model is used to provide loading to the structural components. It is anticipated that results for this model which couples the structure to the fluid will be available for presentation at the 5th SMiRT Conference.

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Table I. Material Properties for Deck Structure Components

	T1 Steel	Concrete
Young's Modulus (GPa)	206	31.7
Poisson's Ratio	0.30	0.18
Yield Stress (MPa)	620	—
Ultimate Stress (MPa)	724	—
Tangent Modulus (MPa)	620	—

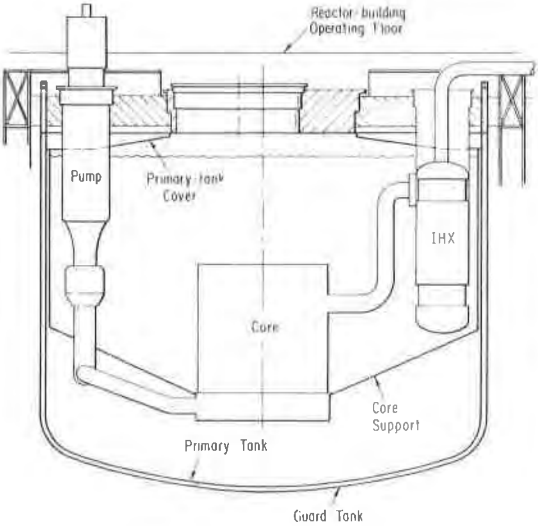

Fig. 1. Reference Pool-Type LMFBR Based on Cold-Pool EBR-II Design (Schematic Elevation View).

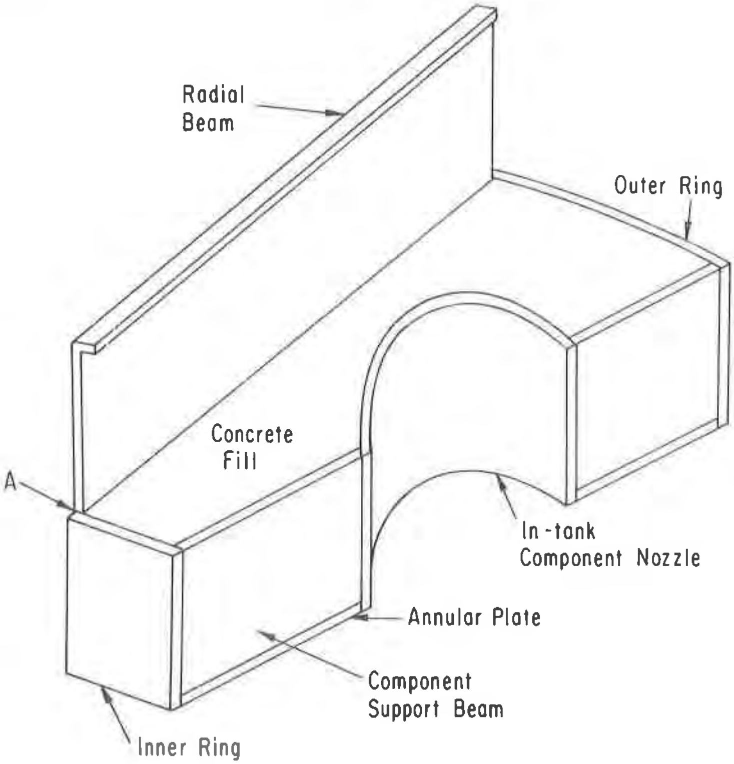

Fig. 2. Sector Model for Pool-Type Deck Structure.

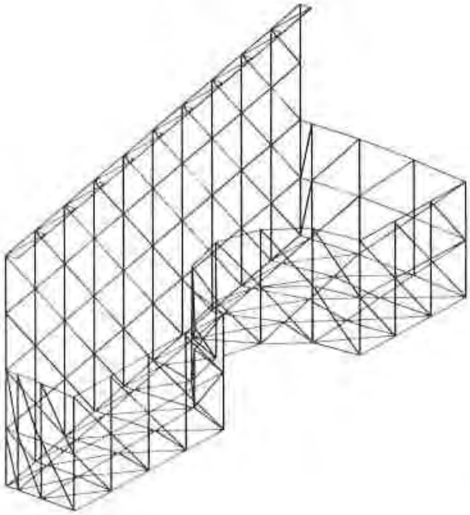

Fig. 3. Complete Structure Plot of Finite-Element Model for the Deck Structure of a 1200 MW(e) Reference Reactor.

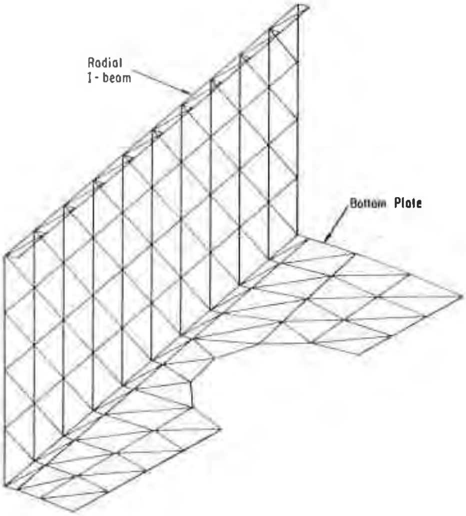

Fig. 4. Finite-Element Discretization of Radial I-Beam and Bottom Plate.

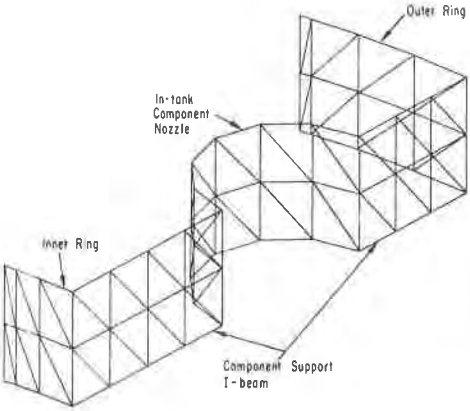

Fig. 5. Finite-Element Discretization of Inner and Outer Rings, Component Nozzle and Component Support Beam.

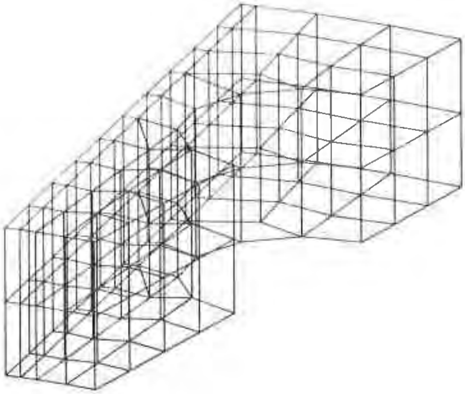

Fig. 6. Discretization of Concrete Fill.

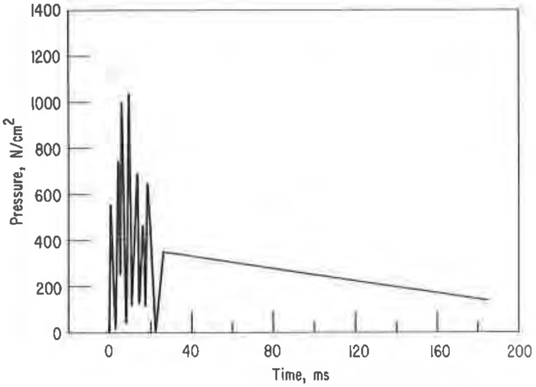

Fig. 7. Pressure Loading on Deck Structure.

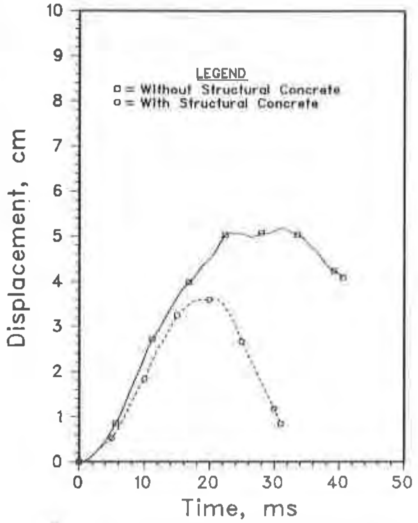

Fig. 8. Vertical Displacement History of the Radial I-Beam at its Connection to the Inner Ring for the Cases with and without the Structural Effect of Concrete.

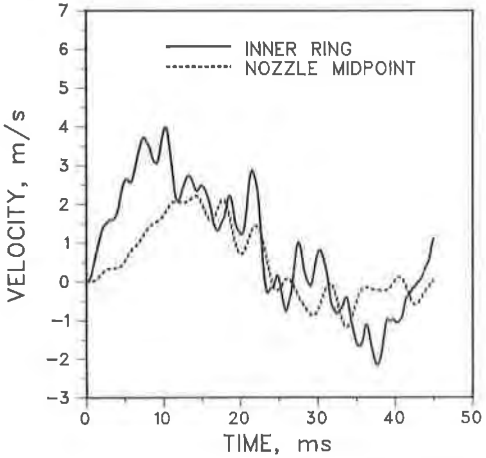

Fig. 9. Velocity Histories of the Inner Ring and the Mid-point of the Nozzle.

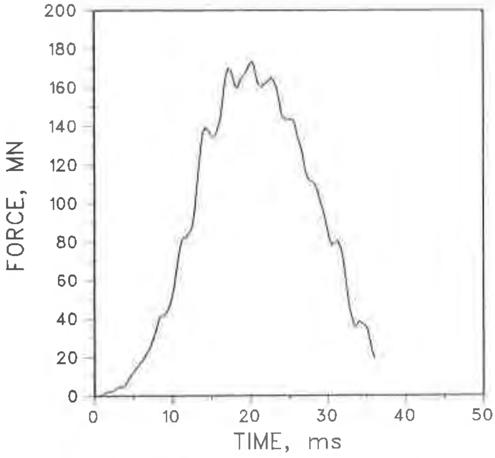

Fig. 10. Vertical Reaction Force Histories of the Column which Support the Main Radial Beam. Structural Effect of Concrete is Taken into Account.