

AN EULERIAN FORMULATION OF FLUID-STRUCTURE INTERACTION
IN
REACTOR CONTAINMENT SYSTEM

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Summary

This paper is concerned with an Eulerian formulation for a fluid-structure interaction developed for the nonlinear fluid-structure interaction analysis of containment and piping components of nuclear reactors. The Eulerian formulation and methodology is chosen because of its decisive abilities for: (1) treating the interaction with large distortions, (2) treating fluid flow around internal structure with geometrical discontinuity, (3) handling wave transients in the vicinity of perforated structure. The ultimate objective is to perform the analysis of the reactor interaction under periodic and transient load.

This Eulerian formulation has been successively linked with various structural hydrodynamic techniques (such as MAC, ICE, IMF, etc.) for analyzing the fluid-structure interaction problems. The resulting computer programs, ICECO, ICE3D, IMF3D have been applied to many reactor safety problems which are reported in the literature. The central feature of the formulation is a generalized method for treating the interface created by the movement of the structure with respect to the stationary Eulerian grid. A coupling technique for the hydrodynamic and structural calculations such that boundary conditions at the fluid-structure interface are rigorously satisfied.

Two types of irregular cells are considered and their formulation corresponding to the ICE technique are described. The first one is for interfaces between coolant and a deformable structure, where the fluid slides tangentially along the moving boundary. A relaxation equation is derived here, allowing the adjustment of the pressure on the moving boundary of the fluid by an amount proportional to the actual mass flux across the boundary. The second irregular cell is for fluid adjacent to the perforated structure where fluid flow through coolant passage takes place. A modified Poisson equation is obtained to appropriately account for the volume perforation and the flow-area availability of the perforated structure. These two equations, in conjunction with the governing Poisson equation of the ICE technique, are solved iteratively. Convergence is attained when boundary conditions at all interfaces are satisfied.

The developed scheme enables the implicit Eulerian hydrodynamic techniques to be coupled with any structural dynamic program. Presently, a corotational coordinate finite element program, WHAMS, is employed for calculating the structural response. Three sample problems are presented to illustrate the analysis. The results are discussed.

I. Introduction

Analysis of fluid-structure interaction is a complex subject since it involves calculations of fluid transients and the resulting structural response. In the safety analysis of nuclear reactors, the problem of fluid-structure interaction is further complicated by the fact that (1) the structural components usually have both geometrical and material nonlinearities; (2) the fluid is almost inviscid and tends to slide along the tangent to the interface; (3) geometrical discontinuities like sharp corners and irregularities may exist in the fluid region; (4) wide spectrum of excursion phenomena such as the wave propagation, sodium slug impact, sodium spillage, expanding gas bubble, as well as two-phase flow and turbulence could occur during an HCBQ; (5) the presence of perforated structures, tube bundles, and elbows usually impose certain difficulties on many numerical techniques. Since there are numerous finite-element structural-dynamics programs available for solving complicated structures with material nonlinearities, the trend of current research thus focuses on the development of effective method to treat the fluid transient and the fluid-structure interaction.

In attempts to solve the coupled fluid-structure problem, substantial research effort has been devoted to the development of numerical techniques and computer codes for performing the analysis of fluid-structure interaction. Conventionally, the Lagrangian and one-dimensional characteristic methods were used in the analysis of reactor containment and piping components, respectively. In the containment analysis, the Lagrangian technique is extremely useful for analyzing the wave propagation, coolant slug impact, and containment response under accident loads. However, it cannot handle strong fluid distortions, such as bubble migration and sodium spillage. Likewise, the characteristic method is quite effective in calculating pressure-pulse propagations in the pipe system. Unfortunately, it cannot give detailed description of the fluid motion inside major piping components like elbow, valve, and heat exchanger.

This paper describes a two-dimensional Eulerian formulation for treating fluid transients and fluid-structure interactions in the primary containment and piping components of nuclear reactors. The emphasis is on the development of a generalized coupling scheme so that a well developed finite-element structural-dynamic program, WHAMS [1], can be linked together with those implicit iterative hydrodynamic techniques, such as the Marker and Cell Method (MAC) [2], Implicit Continuous-fluid Eulerian (ICE) [3] technique, and the Implicit Multi-field (IMF) [4] method. Presently, this coupling scheme has been successively incorporated into both the ICE and IMF techniques for analyzing the fluid-structure interaction problems. The resulting computer programs, ICECO [5], ICEPEL [6], and MICE [7] have been applied to many reactor safety problems which are reported in the literature.

In this paper, a generalized Eulerian method based on the ICE technique is presented. It treats rigorously (1) the sliding boundary condition at the fluid-structure interface, and (2) the fluid motion adjacent to the perforated structures. To illustrate the analysis several sample problems are given and their results are discussed in detail.

2. Description of the Method

2.1 Basic Hydrodynamics

The partial differential equations used in the method are the continuum-mechanics conservation equations of mass, momentum, and energy, and the equation of state of the media. Only nonturbulent flow is considered, and no external energy source is assumed to exist inside the fluid region. The Eulerian coordinates system is used in the formulation, so that the algorithm can be applied to excursions involving arbitrary material distortions.

As suggested by Harlow and Amsden in the ICE technique, the equations of mass and momentum are expressed in the advanced-time forms using an implicit finite-difference representation. Figure 1 shows an Eulerian finite-difference mesh, illustrating the centering of the physical variables relative to a typical cell. The velocities are defined at cell boundaries, u at $i \pm 1/2$ and v at $j \pm 1/2$. Other fluid variables are all defined at the cell center. To simplify the description of the method the detailed derivations of finite-difference expressions of mass and momentum equations will not be presented here, but are given in Ref. [1].

Since elbows of different angles are commonly used to accommodate the various turns of any piping loop, it is important to develop a mathematical model for an elbow structure. Strictly speaking, the analysis of fluid transients in the elbow requires the development of a three-dimensional model. However, a two-dimensional model [2] has been developed to approximate the transient flow in the elbow of any angle, the two dimensions are defined as the radial r -direction and the tangential θ -direction.

2.2 The Fluid-Structure Interface

The interface between the fluid and the deformable structure (such as the core barrel, primary vessel, pipe wall, etc.) is treated as a free surface of the fluid but subject to the pressure distribution that determines its motion. Such interfacial motion is made to coincide with the motion of the structure generated by the internal hydrodynamic pressure loading. Since the viscosity of the fluid (like water or sodium) is very small, the sliding boundary condition is used at the interface which requires that the fluid is allowed to slide along the interface, but in the normal direction, the fluid and the structure are forced to move together.

A convenient way to satisfy the sliding boundary condition is to iteratively adjust the pressure on the fluid interface by an amount proportional to the mass flux rate of the fluid normal to the boundary of the deformable structure. Thus, denoting k and $k+1$ the previous and new iterates, respectively, the relaxation equation for the pressure in the fluid-structure interfacial cell (k, l) is

$$\bar{p}_{k,l}^{h+1} = \bar{p}_{k,l}^h - \frac{\rho \delta}{2\delta\tau} \{(\bar{v}_p - \bar{v}_b) \cdot \bar{n}\}_{k,l} \quad (1)$$

In the above equation, \bar{p} is the advanced-time pressure, ρ is the density, \bar{v}_b is the velocity vector at the midpoint of the structure segment, \bar{v}_p is the velocity vector of the fluid particle, \bar{n} is the unit normal of the boundary pointing into the fluid, τ is the time step, δr and δz are the cell dimensions, and δ is the smallest value between δr and δz . Thus, during the pressure iteration, one can see that if the particles attempt to cross the boundary the pressure in the boundary cell will be increased, forcing fluid to flow away from the boundary and vice versa.

2.3 Treatment of Perforated Structures

The fluid-structure interaction analysis becomes very complicated if one includes all the complex components in the analysis, especially for those structural components containing numerous coolant passageways. They not only redirect the coolant motion, but also impose constraints on the fluid movement and the core-gas bubble expansion. Consequently, the presence of these structural components could have a significant influence on the response of the reactor containment.

To perform the hydrodynamic analysis of a perforated structure a control-volume approach is utilized, which solves the conservation equations of mass, momentum, and energy. For simplicity, we assume that (1) the flow inside the coolant passageways is one-dimensional but viscous, and (2) the available flow areas are lumped along the center line of the Eulerian cell. The basic idea is to use the actual fluid volume and the actual flow area in the control-volume formulation. With this background in mind, a modified Poisson equation for hydrodynamic pressure is obtained, which applies to the region adjacent to the perforated structure. For cell (i, j) located above the perforated structure the corresponding Poisson equation is

$$\bar{p}_{i,j} \left[\frac{1}{c_{i,j}^n} + 2\tau^2 \left(\frac{1}{\Delta r^2} + \frac{1}{\Delta z^2} \right) \right] = H_{i,j} + \tau^2 \left[\frac{r_{i-1/2}}{r_i \Delta r^2} \bar{p}_{i-1,j} + \frac{r_{i+1/2}}{r_i \Delta r^2} \bar{p}_{i+1,j} + \frac{\tau_j}{\Delta z^2} \bar{p}_{i,j-1} + (1-\tau_j) \bar{p}_{i,j} + \bar{p}_{i,j+1} \right], \quad (2)$$

where c is the sonic speed, H is the source term, τ is the area ratio defined as the actual flow area to the area of the respective control surface.

2.4 Fluid-Structure Interaction Involving Multi-Field Flow

The implicit multi-field method (an extended ICE technique) simultaneously relaxes the pressure, density, and velocity components during each iteration. No boundary pressure is needed to determine the pressure in the cell adjacent to a moving structure, as required in the ICE technique which uses the Poisson equation. Once the velocity components on four sides of a cell are defined, the pressure and density in this cell will be adjusted accordingly. Thus, for cells containing a structural segment, the fluid velocity components of each material field are determined from the nonpenetrating condition:

$$(\bar{v}_p - \bar{v}_b) \cdot \bar{n} = 0 \quad (3)$$

In cases where the Eulerian mesh and structural boundary do not coincide, interpolations are required to determine the interface velocity. Such velocity interpolation schemes can be incorporated into existing large scaled multi-field computer codes to perform the fluid-structure analysis involving two-phase flow.

3. Sample Problems

3.1 Shock Tube Problem

To examine the accuracy of the Eulerian method, a shock tube problem is presented. The configuration of the shock tube involves a 100-cm-long, 10-cm-dia cylindrical tube with rigid walls and end caps filled with an ideal gas. The tube is divided into two equal regions of gas by a diaphragm. The internal energies and temperatures on both sides are the same; the density and pressure on the left side are twice the values on the right side. At time $t=0$, the diaphragm is removed. A shock wave initiated at the interface is propagated toward the right side, while a rarefaction wave moves in the opposite direction. The problem is solved by the implicit integration scheme.

Figure 2 presents the pressure profile at $t=500$ μ s after the diaphragm is removed. The result shows no noise at the shock and the rarefaction. Also, the solution is very stable,

even without using any form of viscosity. Figure 3 shows the computed velocity profile at $t=500 \mu s$. Again, the solution is very good.

3.2 Slug Impact and Sodium Spillage

The Eulerian method is employed here to study the slug impact and sodium spillage through the penetration openings on the reactor cover and the ruptured seal. The reactor configuration used in this study is shown in Fig. 4. It consists of a reactor core, a primary vessel, moveable vessel head, and the holddown bolts. The core barrel and the vessel head are assumed to be rigid. Consequently, large impact force is expected and the result is conservative. Two penetration holes are located on the vessel head (shown by dotted lines) to indicate the locations of the leak paths. These penetrations, initially closed, are assumed to open when the impulses at the respective positions reach the prescribed value. The hold-down bolts are assumed to respond elastic-plastically.

Figure 5 presents reactor configurations at 18.0 and 23.0 msec after the impact phenomena after the slug impact. In Fig. 5a the penetrations are closed and the impulses generated by the slug impact and suddenly become open. Figure 5b shows that the reactor cover moved upward and certain amounts of coolant already spilled out through the penetrations and the side opening at the vessel-cover junction. The impact is completed at about 23 msec at which time the primary containment already ruptured and the sodium spillage. The sodium-spillage analysis is of great importance to the transient analysis related to the secondary containment.

3.3 The Effect of the Upper Internal Structure on the Containment Response

This example investigates the effect of the upper-core internal structure on the slug impact and containment response during an HCDA. It compares the results of two cases, one with this particular structure and the other without. Figure 6 shows the reactor configuration (with the upper-core internal structure) used in the analysis. The problem system is discretized into 10×28 meshes. Here, we present some results of this analysis.

Figure 7 gives the reactor configuration at 24 msec for the case with the upper-core internal structure. Significant flow blockage near the lower plate can be clearly seen in this figure. The upper-core internal has pronounced mitigating effect on the slug impact loading. For the calculation without this structure the peak impact force is 33.7×10^6 N. However, for the case with this structure the peak value is only 11.0×10^6 N. Moreover, the comparison reveals that in the case with the upper internal the HCDA gas-bubble volume, the axial velocity of the sodium slug, the axial kinetic energy of the fluid, and the upper vessel deformation are considerably reduced compared to the respective values for the case with out this structure. Thus, this study demonstrates that the upper internal structure has capability of confining the HCDA bubble expansion, slowing down the upward motion of the sodium slug, as well as reducing the slug impact loading.

4. Conclusions

It has been demonstrated that the Eulerian formulation described previously is capable of analyzing the two-dimensionally fluid transient and fluid-structure interactions in the primary containment and piping components. The generalized hydrodynamic scheme developed facilitates the treatment of the irregular cells created by the movement of the structure and avoids the complex procedures at the fluid structure interface.

The method has several special features. First, it provides a rigorous hydrodynamic analysis at the fluid-structure interface where the sliding boundary condition is satisfied.

Second, it uses an effective approach for treating wave propagation near the perforated structure. Third, the interfacial treatment can be easily incorporated into the ICE type multi-field methods to perform the coupled fluid-structure analysis involving the two-phase flow.

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Fig. 1. The Location of the Cell Variables in a Eulerian Computational Cell.

Fig. 2. Pressure Profile at $t=500 \mu s$.

Fig. 3. Velocity Profile at $t=500 \mu s$.

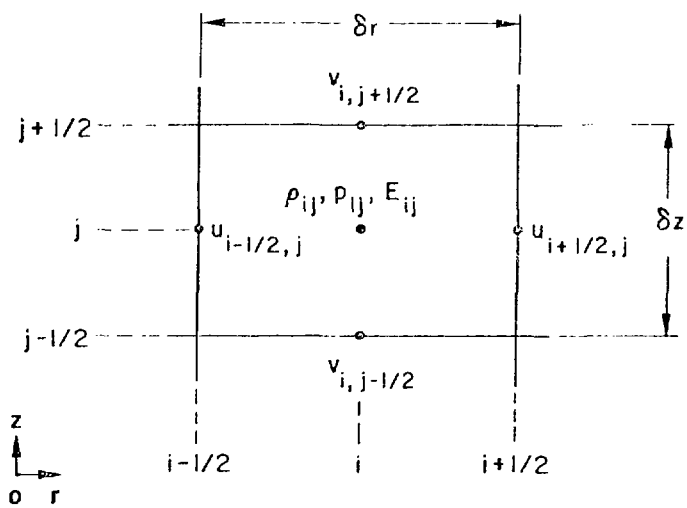
Fig. 4. Initial Configuration Used for Slug Impact and Sodium Spillage Analysis.

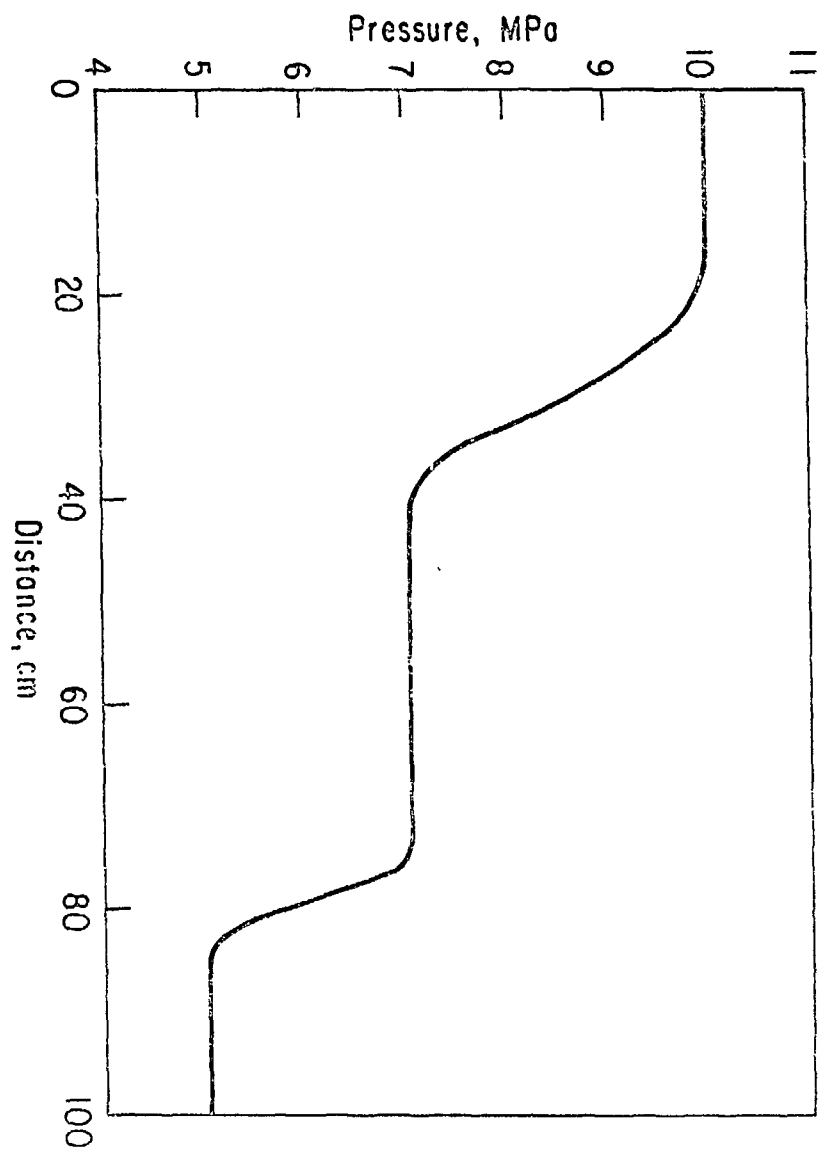
Fig. 5. Reactor Configurations at Two Different Times.

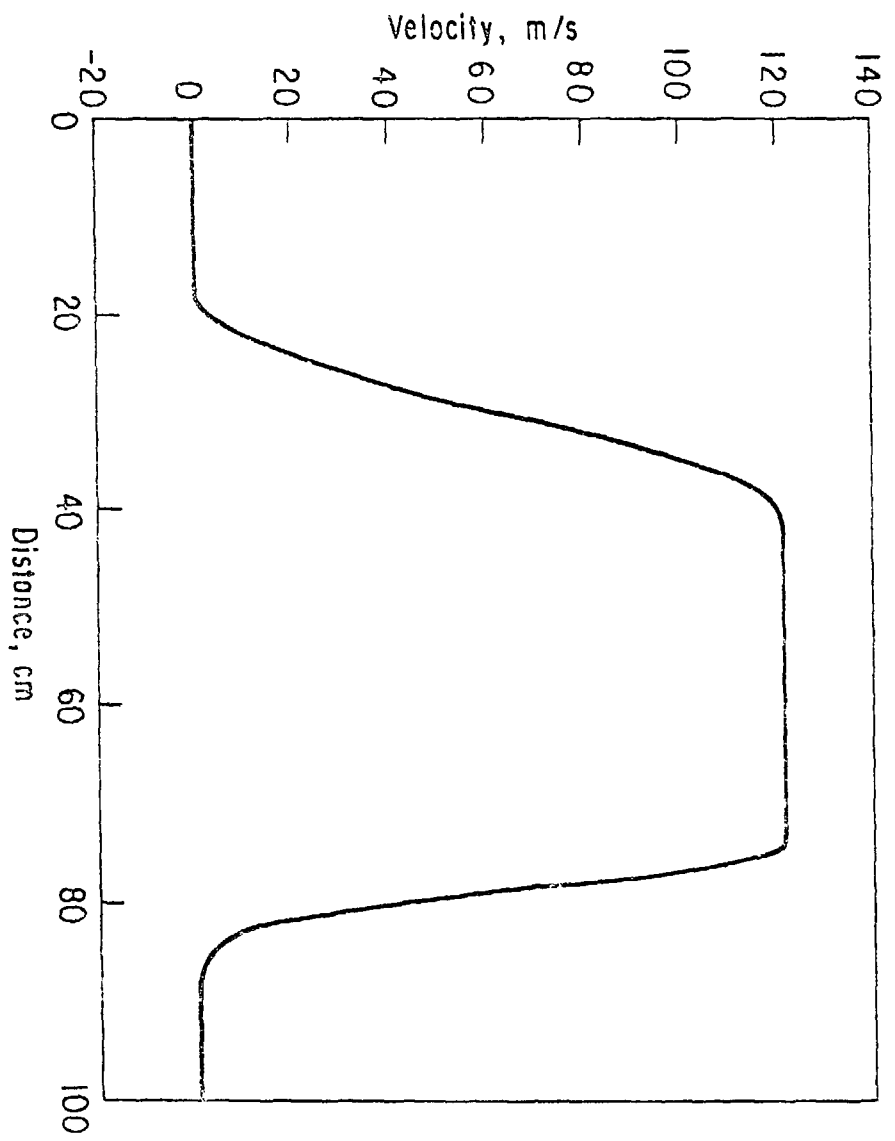
Fig. 6. Initial Reactor Configuration for Calculation with Upper Internal Structure.

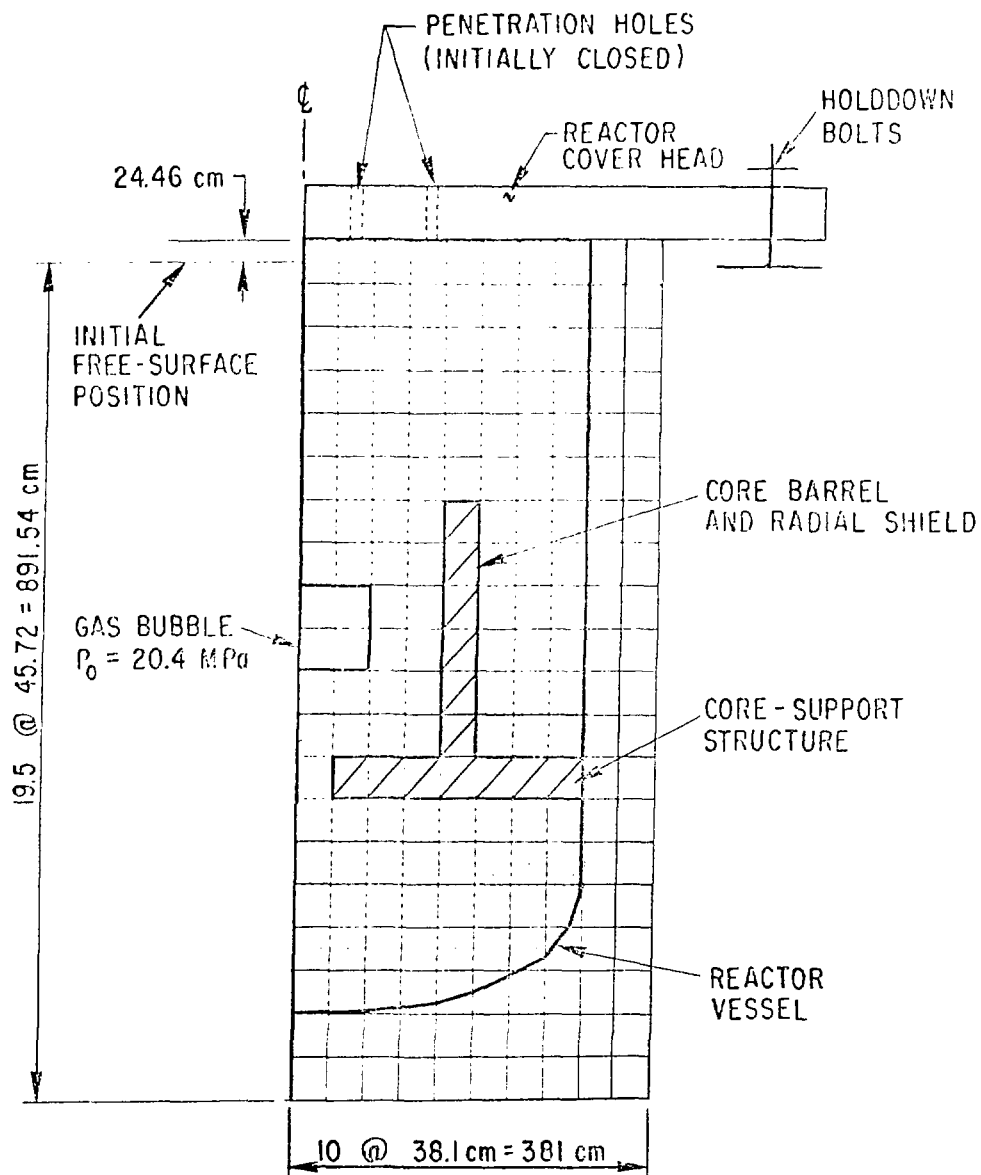
Fig. 7. Reactor Configuration at 24 ms (with Upper Internal Structure).

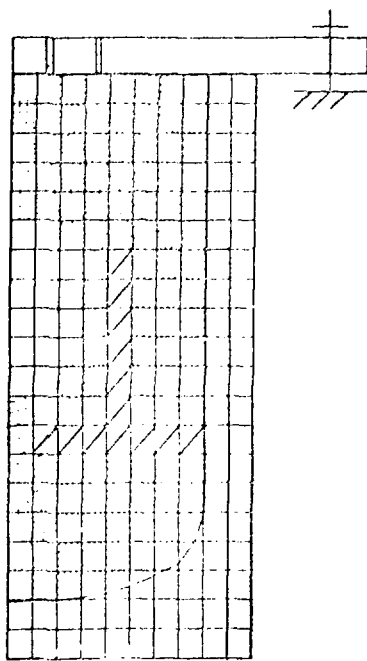
CELL (i, j)



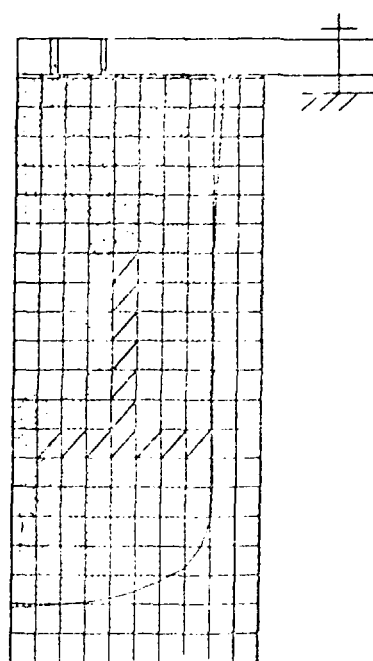




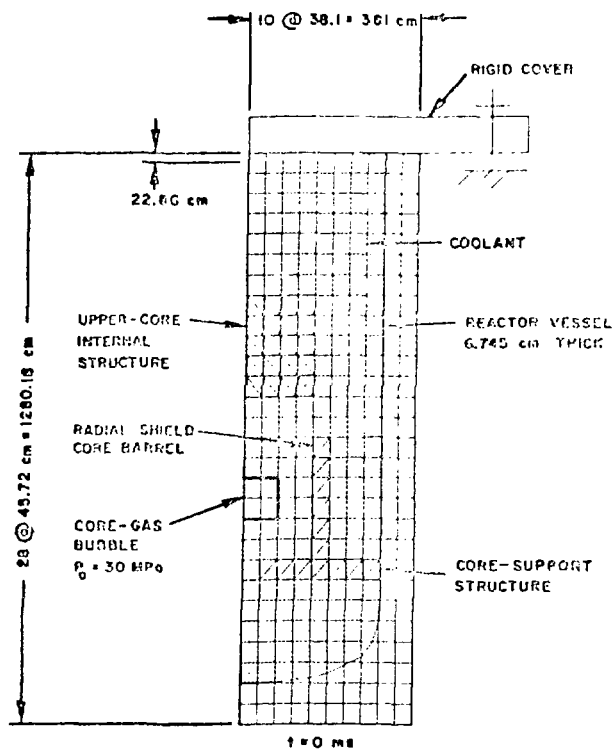


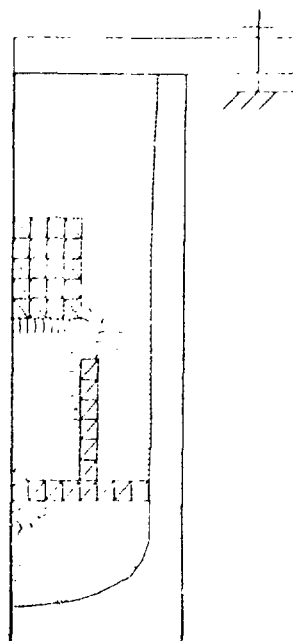


$t = 18.9 \text{ ms}$



$t = 22.6 \text{ ms}$





$t = 24 \text{ ms}$