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ANALYSIS OF LMFBR PRIMARY SYSTEM RESPONSE
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Abstract

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1. Introduction

Even though large liquid-metal fast breeder reactors (LMFBRs) can be designed for safe and reliable operation, the safety assessment of the reactor design requires an analysis of the capability of the reactor primary system to sustain the consequences of a hypothetical core disruptive accident (HCDA). Analytical methods developed for safety analysis must, therefore, be able to analyze all the physical phenomena included in the HCDA.

The excursion phenomena in a hypothetical core disruptive accident in an LMFBR can be, in general, described as follows: First, core energy is transmitted to the adjacent media by pressure waves. As a result of the propagation of the pressure waves and the core expansion, coolant moves in the direction of least resistance. In a typical reactor configuration, significant movement of the coolant is encountered in the upward axial direction above the core. When the coolant slug suddenly comes into contact with the reactor cover, a large impact force is produced on the head cover and upper vessel wall. The cover could lift and allow the release of coolant into the secondary containment. When the impact pressure reflects back into the coolant and encounters the expanding core-gas bubble, the bubble may become unstable and break into numerous small bubbles which may mix with the coolant and release into the secondary containment. The pressure waves generated also propagate through piping loops of the primary coolant system in a looped LMFBR and may cause damage to loop components.

Primary containment is designed to sustain the pressure waves and the slug impact force; secondary containment is to contain the radioactive gas and aerosol from releasing to the surrounding environs. Assurance of their integrity is of primary importance in the fast reactor safety analysis. Since the primary coolant system is a part of the primary boundary its integrity is also a concern in the safety analysis. The computational methods and computer codes developed for analyzing the excursion phenomena are almost invariably utilizing the Lagrangian coordinates system. Although these codes have been successfully used to analyze the wave propagation, slug impact, and the containment response under accident loads, the Lagrangian analyses are still limited to the early stage of gas-bubble expansion because of Lagrangian-zone distortions. For problems involving large material distortions such as bubble contraction and collapsing, as well as sodium spillage, reliable results can only be obtained by the method of solution using the Eulerian coordinates system.

This paper describes the applications of the Eulerian code to predict the response of the fast reactor containment and the primary piping loops to HCDAs, and to analyze the sodium-spillage problem, which cannot be analyzed with a Lagrangian code. More specifically, the computer code used for analyzing the primary system response is the expanded version of the Implicit Continuous Eulerian Containment code, ICECO, developed at ANL, which uses the implicit treatment of the density variation of the ICE technique[1] and is applicable to both compressible and incompressible flows. For excursion magnitude in any ranges, the technique always offers a stable and accurate numerical solution. Particularly, the code is suitable for the long-duration calculation of problems involving large material distortions.

The base equations and numerical techniques have been discussed by Wang et al.[2]. This paper extends the method to treat (1) irregular cells and arbitrarily-shaped boundaries in a reactor configuration which contains a curved reactor vessel, (2) sodium-spillage through penetration openings on the reactor head and wall openings at the head junction generated by slug impact, and (3) the response of the primary piping loop that consists of straight pipes, elbows, and other components connected in series and subject to HCDA loads at both ends of the loop.

2. Description of the Implicit Eulerian Code

2.1 The Basic ICECO Code

2.1.1 Hydrodynamic Equations

The partial differential equations used in the method are the continuum-mechanics conservation equations of mass, momentum, energy, and the equation of state of the media. These equations are written in cylindrical coordinates with axial symmetry. Only nonturbulent flow is considered in the analysis, and no external energy source is assumed to exist inside the fluid region. Thus,

denoting the radial and axial coordinates by r and z , respectively, and the corresponding radial and axial velocity components by u and v , the mass equation of a viscous, compressible fluid is

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial \rho u r}{\partial r} + \frac{\partial \rho v}{\partial z} = 0 \quad (1)$$

where ρ is fluid density, t is the time.

The momentum equations, including nonlinear convective and viscous diffusion terms, in the radial and axial directions are, respectively

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r} \frac{\partial \rho u^2 r}{\partial r} + \frac{\partial \rho u v}{\partial z} = \rho g_r - \frac{\partial}{\partial r} (p + q) + \mu \frac{\partial}{\partial z} \left(\frac{\partial u}{\partial r} - \frac{\partial v}{\partial r} \right), \quad (2)$$

and

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r} \frac{\partial \rho u v r}{\partial r} + \frac{\partial \rho v^2}{\partial z} = \rho g_z - \frac{\partial}{\partial z} (p + q) - \frac{\mu}{r} \frac{\partial}{\partial r} \left[r \left(\frac{\partial u}{\partial z} - \frac{\partial v}{\partial r} \right) \right] \quad (3)$$

where

$$q \equiv -(\lambda + 2\mu) \left(\frac{1}{r} \frac{\partial u r}{\partial r} + \frac{\partial v}{\partial z} \right) \quad (4)$$

is the viscous pressure, g_r and g_z are the two components of gravitational acceleration, p is the pressure, μ and λ are, respectively, the first and second viscosity coefficients. These coefficients sometimes can be used as "artificial viscosities" to eliminate the shock discontinuities and numerical instabilities.

The energy equation has the form

$$\begin{aligned} \frac{\partial \rho E}{\partial t} + \frac{1}{r} \frac{\partial \rho u E r}{\partial r} + \frac{\partial \rho v E}{\partial z} = & \rho u g_r + \rho v g_z + \frac{1}{r} \frac{\partial}{\partial r} \left\{ r \left[B\mu \frac{\partial I}{\partial r} - p u - \left(\frac{\lambda}{\lambda + 2\mu} \right) q u \right. \right. \\ & \left. \left. + \frac{\mu}{2} \frac{\partial}{\partial r} (2u^2 + v^2) + \mu v \frac{\partial u}{\partial z} \right] \right\} + \frac{\partial}{\partial z} \left\{ B\mu \frac{\partial I}{\partial z} - p v \right. \\ & \left. - \left(\frac{\lambda}{\lambda + 2\mu} \right) q v + \frac{\mu}{2} \frac{\partial}{\partial z} (u^2 + 2v^2) + \mu u \frac{\partial v}{\partial r} \right\}, \end{aligned} \quad (5)$$

in which

$$E \equiv I + (u^2 + v^2)/2 \quad (6)$$

is the specific total energy, and I is the specific internal energy. The temperature term in the energy equation has been eliminated by using the relations.

$$\kappa \frac{\partial T}{\partial x_i} \equiv \mu B \frac{\partial I}{\partial x_i} \quad \text{and} \quad B = \frac{\gamma}{P_r} \quad (7)$$

in which T is the temperature, κ is the thermal conductivity, γ and P_r are, respectively, the gas exponent and Prandtl number of the fluid.

The equation of state can be expressed in a general form

$$\rho = f(p, I). \quad (8)$$

2.1.2 Finite Difference Equations

The ICECO code employs an implicit treatment of the finite-difference representations to the set of nonlinear differential equations mentioned above. In the mass equation, convective fluxes are expressed as functions of the unknown advanced-time densities and velocities. The pressure gradients in the momentum equations is expressed as a function of the unknown advanced-time pressure. These treatments not only ensure the stability of the numerical method with respect to sound-signal propagation, but also considerably ease the Courant restriction on the time step used for the numerical integration.

The principal feature of the Implicit Eulerian method is to use the implicit expression of density variation in the equation of state of the media. Thus, expressing in the finite-difference form, the equation of state is

$$p_{i,j}^{n+1} \equiv p_{i,j}^n + c_{i,j}^n (\rho_{i,j}^{n+1} - \rho_{i,j}^n), \quad (9)$$

where

$$c_{i,j}^n \equiv \left(\frac{\partial p}{\partial \rho} \right)_{i,j}^n$$

is related to the speed of sound. Equation (9) means that the unknown advanced-time pressure depends implicitly on the density variation, but can remain purely explicit for the internal energy. Also, in eq. (9), the superscripts $n+1$ and n denote the $(n+1)$ -th and the n -th time cycles, while subscripts i, j indicate spatial values.

The procedure for determining the advanced-time pressure is to rigorously conserve mass for every cell. Thus, eliminating all the advanced-time densities and velocities in the difference form of mass equation by using eq. (9) and difference equations of eqs. (2) and (3), one obtains a Poisson equation:

$$\begin{aligned} p_{i,j}^{n+1} \left[\frac{1}{c_{i,j}^n} + 2\delta t^2 \left(\frac{1}{\delta r^2} + \frac{1}{\delta z^2} \right) \right] \\ = G_{i,j}^n + \delta t^2 \left[\frac{r_{i-1/2} p_{i-1,j}^{n+1} + r_{i+1/2} p_{i+1,j}^{n+1}}{r_i \delta r^2} \right. \\ \left. + \frac{p_{i,j-1}^{n+1} + p_{i,j+1}^{n+1}}{\delta z^2} \right], \end{aligned} \quad (10)$$

where

$$G_{i,j}^n = G(u^n, v^n, p^n, \mu, \lambda, \delta t, \delta r, \delta z)$$

is the source term evaluated from previous cycle values, δt is the time step, δr and δz are, respectively, the dimensions of a cell in the radial and axial directions.

It should be mentioned that eq. (10) is the governing difference equation for the advanced-time pressure, and is expressed in the implicit version. It is a five point equation that is solved by the iteration technique.

In the iteration process, a much improved formula is used by replacing $(p_{i-1,j}^{n+1})^h$ and $(p_{i,j-1}^{n+1})^h$ with the latest iterates $(p_{i-1,j}^{n+1})^{h+1}$ and $(p_{i,j-1}^{n+1})^{h+1}$ while sweeping in the direction of increasing i and j . This yields

$$\begin{aligned} (p_{i,j}^{n+1})^{h+1} \left[\frac{1}{c_{i,j}^n} + 2\delta t^2 \left(\frac{1}{\delta r^2} + \frac{1}{\delta z^2} \right) \right] \\ = G_{i,j}^n + \delta t^2 \left[\frac{r_{i-1/2} (p_{i-1,j}^{n+1})^{h+1} + r_{i+1/2} (p_{i+1,j}^{n+1})^h}{r_i \delta r^2} \right. \\ \left. + \frac{(p_{i,j-1}^{n+1})^{h+1} + (p_{i,j+1}^{n+1})^h}{\delta z^2} \right]. \end{aligned} \quad (11)$$

where h and $h+1$ denote previous and latest iteration, respectively.

To check the numerical accuracy, one can calculate the advanced-time energies using the difference expressions of eqs. (5) and (6). The detailed derivations of finite-difference expressions of mass and momentum equations are given in references [1], [2], and [3].

2.2 ICECO Extensions

2.2.1 Treatment of the Deformable Containment Walls

In the basic ICE method, the containment wall can only be treated as rigid; in ICE method extensions, the containment wall can be considered either as rigid or as deformable. In the deformable wall analysis, the reactor containment is treated as a shell of revolution. The governing differential equations are:

$$\begin{aligned} \frac{\partial}{\partial s} [N_{\phi} r \cos \phi] - \frac{\partial}{\partial s} [Q_{\phi} r \sin \phi] - N_{\theta} + p r \sin \phi - m \ddot{r} &= 0, \\ \frac{\partial}{\partial s} [N_{\phi} r \sin \phi] + \frac{\partial}{\partial s} [Q_{\phi} r \cos \phi] - p r \cos \phi - m \ddot{r} &= 0, \\ \frac{\partial}{\partial s} [M_{\phi} r] - M_{\theta} \cos \phi - Q_{\phi} r &= 0, \end{aligned} \quad (12)$$

where s is the length of the shell along the meridian; measured from the vertex of the shell, m is the mass of the shell per unit area, ϕ is the angle of inclination of the element with respect to the r direction, p is the pressure, N_{ϕ} and N_{θ} are two tangential stress resultants, and Q_{ϕ} is the transverse stress. The shell is idealized by layers of subshells that can carry only normal stresses in the planes parallel to the tangential plane of the shell structure. These subshells are connected by the material that carries only shears. The vessel material is considered to be elastic-plastic, strain hardening. The strain-hardening shell is represented by a model in which the thickness of the subshell is further decomposed into subregions of elastic-perfectly-plastic materials having different yield stresses, but common strains. The von Mises yield condition is used.

In the analysis, the motion of an interface between coolant and the deformable containment vessel (or other movable structures, such as vessel cover in the case of slug impact problem) is equivalent to that of a free surface with an applied pressure distribution. Given any interfacial shape or motion one can produce that shape or motion with some unique pressure distribution applied to a free surface. Since the implicit Eulerian method already has a technique for treating free surfaces, it is only necessary that one find a way of relating the required pressure distribution to the motion and shape of the boundary.

A moving wall can be specified by a locus of node points described by the Lagrangian coordinates, as shown in Fig. 1a. These nodes move across the fixed Eulerian mesh and their positions are determined by the equations of a thin shell or other movable structures.

The viscous effect is neglected at the wall boundary. The method treats the moving wall in such a way that the fluid slips along the wall, but in the direction normal to the wall boundary the fluid and the solid wall are forced to move together. Thus, for each cell that contains the moving boundary (see Fig. 1b), the inviscid boundary condition yields

$$(\bar{v}_p^{n+1} - \bar{v}_b) \cdot \bar{n} = 0 \quad (13)$$

In this equation, $\bar{v}_p^{n+1}$ is the velocity vector of a virtual particle located at the midpoint of the wall segment, $\bar{v}_b$ is the velocity vector of the moving boundary obtained from the structural mechanics calculation, and $\bar{n}$ is the unit normal vector pointing into the fluid region.

A more convenient procedure to solve eq. (13) in the boundary cell is to express that equation in terms of the advanced-pressure field; then eqs. (13) and (11) can be solved together.

One way of doing this is by introducing the relaxation parameter ΔT and the following iteration formula for the $h+1$ iteration value of the advanced-pressure field:

$$(p_{k,l}^{n+1})^{h+1} = (p_{k,l}^{n+1})^h - \frac{\Delta T}{\delta} \left\{ \left[(\bar{v}_p^{n+1})^h - \bar{v}_b \right] \cdot \bar{n} \right\}_{k,l} \quad (14)$$

in which

$$\delta = \max[\delta r, \delta z]$$

and

$$\Delta T \leq \rho_{k,l} \delta^2 / 26t$$

In eq. (14) the subscripts k and l refer to the boundary cell (k, l) having the vessel segment, $(\bar{v}_p^{n+1})_{k,l}^h$ is a new iterate that must be recomputed each time the pressures and velocities are adjusted. The particle velocity is computed from an interpolation formula[3].

Note that by continued iteration process, eq. (14) is just the asymptotic solution of eq. (13). Also 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.

The procedure for a computation cycle is as follows: (i) calculate the source term $G_{1,j}^n$ of the Poisson equation from previous cycle values (ii) if the containment wall is deformable, calculate the advanced-time pressure field by eqs. (11) and (14). Substitute the new pressures into eq. (9) and obtain advanced-time densities. Compute advanced-time velocities from difference expressions of Eqs. (2) and (3). Finally, calculate the particle-velocity vector in the boundary cell by using the latest iterates of advanced-time velocities. Continue these steps until changes in the iterate fall below the convergence criterion. (iii) if the containment wall to be considered is rigid, solve advanced-time pressures by iterating eq. (11). (iv) after convergence of advanced-time pressure field is achieved, compute the advanced-time density, velocities, total energy, and internal energy using eq. (9) and finite-difference equations of eqs. (2), (3), (5), and (6).

2.2.2 Treatment of the Sodium Spillage

The Eulerian hydrodynamics is ideal for long-duration calculations for problems involving large material distortions. The basic ICE technique has an option for treating in-flow and out-flow boundary conditions. Figure 2 is a sequence of reactor configurations showing the spillage of coolant through an opening at the top of the containment wall using the ICE technique. However, the size of the wall opening in the basic ICE method is limited to multiples of the mesh size. In other words, if the wall opening is small, the Eulerian mesh size must also be made small accordingly. In addition, the size of the opening in the basic ICE technique must remain constant. In other words, the opening does not vary with time, which is different from a gap generated by the slug impact force on the reactor head cover at the head-vessel junction. Therefore, the basic ICE technique must be expanded in order to treat the coolant spillage problem more realistically.

An irregular-cell method is therefore incorporated into the ICECO extension for treating openings whose size varies. When the slug-impact once exceeds the hold-down bolt force or when the head moves upward, a set of irregular cells is introduced on the top of the full-zone regular cells as shown in Fig. 3. The sizes of irregular cells in the axial direction are assumed to vary with the head displacement. The variables in the two fictitious zones, one above the regular cells and one below the irregular cells (see Fig. 3b and 3c), are linearly interpolated after each iteration. The tops of the irregular cells are considered as a free-slip boundary, moving with the same velocity as the cover head.

For openings whose size is smaller than the side of the regular cell as shown in Fig. 4, the governing equations are finite-differenced with respect to three subcells (see Fig. 4).

For simplicity, it has been further assumed that: (1) small openings are only located on the top center of the irregular cells as shown in Fig. 5; (2) only one opening is allowed for each cell; and (3) the opening is considered to be closed initially and become open when the impulse on the opening exceeds a certain input value. With these assumptions, the Poisson equation becomes

$$\begin{aligned}
 p_{i,j}^{n+1} & \left[\frac{1}{c_{i,j}^n} + 2\delta t^2 \left(\frac{1}{\delta r^2} + \frac{1}{\delta z^2} \right) \right] \\
 & = G_{i,j}^n + \delta t^2 \left[\frac{r_{i-\frac{1}{2}} p_{i-1,j}^{n+1} + r_{i+\frac{1}{2}} p_{i+1,j}^{n+1}}{r_i \delta r^2} \right. \\
 & \quad \left. + \frac{p_{i,j-1}^{n+1} + y_i p_{o,i,j+1}^{n+1} + (1-y_i) p_{i,j+1}^{n+1}}{\delta z^2} \right]
 \end{aligned} \quad (15)$$

where y_i = percentage of the opening area on top of cell i,j ; $p_{o,i,j+1}$ = pressure outside the opening; $G_{i,j}^n = G(u^n, v^n, p^n, \mu, \lambda, \delta t, \delta r, \delta z, y_i, v_o^n)$, and with v_o^n = fluid velocity at the opening.

2.2.3 Treatment of the Piping Loop

A piping loop consists of straight pipes, elbows, and other components. The basic hydrodynamic equations employed in the ICECO code are expressed in r - z directions. They cannot be used for analyzing elbows. Strictly speaking, the analysis of the transient fluid dynamics in the elbow requires the development of a three-dimensional model. However, a two-dimensional model can be developed to approximate the transient flow in the elbow if the secondary flow in the elbow is small and can be ignored. The two dimensions considered are the radial r -direction, radially outward from the center of curvature of the elbow, and the tangential θ -direction, as shown in Fig. 6 where the Eulerian mesh of the elbow is also shown.

The conservation equations of mass, momentum, and energy are:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r\eta} \frac{\partial(r\rho u)}{\partial r} + \frac{1}{r} \frac{\partial(\rho v)}{\partial \theta} = 0, \quad (16)$$

$$\begin{aligned}
 & \frac{\partial(\rho u)}{\partial t} + \frac{u}{\eta} \frac{\partial(\rho u)}{\partial r} + \frac{1}{r} \frac{\partial(\rho u v)}{\partial \theta} + \rho \left(\frac{1}{2} \frac{\partial u^2}{\partial r} - \frac{v^2}{r} + \frac{u^2 \ell}{r\eta} \right) \\
 & = \frac{\rho}{r} - \frac{\ell}{\eta} \frac{\partial}{\partial r} \left(p + \frac{\lambda q}{\lambda + 2\mu} - 2\mu \frac{\partial u}{\partial r} \right) + \frac{\lambda}{\lambda + 2\mu} \frac{q}{r} + \frac{1}{r} \frac{\partial}{\partial \theta} \left(H - \frac{2\mu v}{r} \right) - 2\mu \frac{u}{r^2},
 \end{aligned} \quad (17)$$

$$\begin{aligned}
 & \frac{\partial(\rho v)}{\partial t} + \frac{v}{\eta} \frac{\partial(\rho u)}{\partial r} + \frac{\rho u}{r} \frac{\partial(rv)}{\partial r} + \frac{1}{r} \frac{\partial(\rho v^2)}{\partial \theta} + \frac{\rho u v \ell}{r\eta} \\
 & = \frac{1}{r} \frac{\partial}{\partial \theta} (p + q) + \frac{1}{r\eta} \frac{\partial(r\lambda H)}{\partial r} + \frac{H}{r} + \frac{2\mu}{r^2} \frac{\partial}{\partial \theta} \left(u - \frac{1}{\eta} \frac{\partial(ru\ell)}{\partial r} \right)
 \end{aligned} \quad (18)$$

$$- 2\mu \frac{\xi(r)}{\eta} \left| \frac{R-r}{r_o} \frac{v}{r} \right| \frac{|v|}{v},$$

$$\begin{aligned}
& \frac{\partial(\rho E)}{\partial t} + \frac{1}{r} \frac{\partial(\rho v E)}{\partial \theta} + \rho u \frac{\partial E}{\partial r} + \frac{E}{r\eta} \frac{\partial(\rho r u l)}{\partial r} \\
& = \frac{1}{r} \frac{\partial}{\partial r} \left[r l \left\{ - p u - \frac{\lambda}{\lambda + 2\mu} q u + 2\mu u \frac{\partial u}{\partial r} + v H \right\} \right] \\
& + \frac{1}{r} \frac{\partial}{\partial \theta} \left[- p v - \frac{\lambda}{\lambda + 2\mu} q v + 2\mu u \left(\frac{1}{r} \frac{\partial}{\partial \theta} + \frac{u}{r} \right) + u H \right] \\
& - 2\mu \frac{\xi(r)}{\eta} \left| \frac{R-r}{r_o} \frac{\partial v}{\partial r} v \right|, \tag{29}
\end{aligned}$$

where l is the length of the cord of the circular cross section of the elbow, r_o the radius of the cross section of the elbow, R the radius of the curvature of the elbow, u and v the radial and tangential velocity components, and

$$q = -(\lambda + 2\mu) \left(\frac{1}{r\eta} \frac{\partial(rul)}{\partial r} + \frac{1}{r} \frac{\partial v}{\partial \theta} \right),$$

$$H = \mu \left[r \frac{\partial}{\partial r} \left(\frac{v}{r} \right) + \frac{1}{r} \frac{\partial u}{\partial \theta} \right],$$

$$\eta = \frac{A_\theta}{\delta r} \quad (\text{refer to Fig. 2}),$$

$$\xi(r) = \frac{A_w}{r\delta r\delta\theta} = 1 + \frac{1}{2} \left(\frac{r-R}{r_o} \right)^2 + \frac{1.3}{2.4} \left(\frac{r-R}{r_o} \right)^4 + \frac{1.3.5}{2.4.6} \left(\frac{r-R}{r_o} \right)^6 + \dots,$$

with

A_θ = Eulerian zone area normal to the θ -direction,

A_w = elbow wall area,

δr = interval size in the r -direction, and

$\delta\theta$ = interval size in the θ -direction.

The detail derivation of these equations is given in [4]. The elbow wall is assumed to be rigid.

The basic assumption used in the ICECO extension loop analysis is that the flow inside the pipes and other components (except elbow) remains axially symmetric. Because of the shape of the Eulerian zones in the axisymmetric models is different from that in the elbows, the coupling of the two models presents a difficulty in the junctions between these models. As can be seen, in applying the Poisson's equation at the pipe zones next to the junction, one requires a column of fictitious zones outside the pipe. The field variables in these zones are related to the connecting elbow. The same is true for the elbow fictitious zones. However, as mentioned above, the pipe zones are in rings and the elbow zones are in strips. The field variables in the pipe fictitious zones cannot be taken directly from the appropriate elbow zones or vice versa. The technique used here determines the pressure in the fictitious zones in such a way that: (1) the continuity of the mass flow rate across the interconnected ring and strip is satisfied; (2) the total force exerted by the pressures in the fictitious zones of the pipe is equal to the total force exerted by the pressure in the connecting elbow zones; (3) the total force exerted by the pressures in the fictitious zones of the elbow on the junction is equal to the total force exerted by the pressures in the connecting pipe zones. Again, detailed description regarding the coupling process is given in [4].

3. Sample Problems

To illustrate the application of the Eulerian code to predict the response of the reactor primary system to an HCDA, three sample problems are given below. The first problem deals with the slug impact and sodium spillage. The second problem deals with the dynamics of the HCDA bubbles. The third problem deals with the response of a piping loop that consists of six elastic-plastic pipes with five rigid elbows connected in series and subjected to pressure pulses at both ends of the loop.

3.1 Slug Impact and Sodium Spillage

To understand the effect of the wall opening and sodium spillage on the slug-impact force, coolant motion, and wave propagation, the expanded ICECO code was employed to a reactor configuration consisting of deformable wall, movable head, and holddown bolts as shown in Fig. 7. The vessel wall was made of three-inch stainless steel. The initial pressure in the core region was assumed to be 300 bars. Two computations were performed. One assumed no gap opening as the reactor head was moving upward, while the other assumed that a gap opening was generated and resulted in sodium spillage into the secondary containment.

Figures 8 and 9 show, respectively, the time histories of the total force on the vessel cover and pressure at zone (6,14), where the solid line represents the results with sodium spillage, and the dashed line without sodium spillage. These figures show that in the case with wall opening and sodium spillage, both the peak force and the peak pressure have been reduced. They also show, as anticipated, that the reduction in both the peak force and pressure increases with increasing size of the wall opening as the excursion continues.

Figure 10 presents the reactor and coolant configurations at three instants. These configurations show the deformation of the vessel wall before and after the slug impact, and the upward motion of the reactor cover. The overall coolant motion and the bubble motion can be clearly seen. It is observed that during the time interval between 7.25 and 24.75 msec the coolant motion and bubble position change substantially. This information seems important in the safety evaluation of a containment system.

3.2 Dynamics of the HCDA Bubbles

A concern in the LMFBR safety analysis is the final disposition of the gas bubble after it has produced damage to the reactor primary system. The gas bubble may collapse into numerous small bubbles under the intense pressure waves produced by the slug impact on the reactor head, or it may surface upward immediately following the excursion to produce a thermal loading on the head cover. Thus, it is important that the safety analysis of containment system can investigate all stages of the bubble motion from expansion, contraction, migration, and reconstruction to bubble collapsing or surfacing.

As a preliminary study, bubble motions and subsequent wave propagations in two different geometries were investigated by the expanded ICECO code. The purpose of this study is to examine the conditions under which the gas bubble could surface upward, without being severely distorted or collapsed into numerous small bubbles, to produce a thermal loading on the reactor cover.

The mathematical model chosen in the analysis is shown in Fig. 11. Two cases are considered. Case 1 examines a relatively deep excursion in which the initial free-surface height is 611.4 cm. Case 2 considers a shallow-coolant excursion where the initial bubble position is very close to the free surface, with the initial free-surface height equal to 448 cm. In both cases, the initial bubble shapes are assumed to be rectangular. The source pressure at the beginning of excursion is 204 bars. Motion is started in an otherwise quiescent, compressible fluid.

Figures 12 and 13 show the calculated bubble configurations at several different instants, corresponding to the relatively deep excursion and shallow coolant excursions, respectively. From these results, we observed several interesting features: (a) in both cases, a ring vertex or jet-like spike is generated at the bubble bottom. This jet of coolant, caused by the boundary proximity and the strong pressure wave reflected from the bottom plate, persists throughout the remainder of the

motion and changes bubble shapes to toroidal. (b) in the case of relatively deep excursion, the upper bubble surface is quite smooth before the slug impact. However, after the slug impact, several spikes are generated at the top surface of the gas bubble. Dynamically, the spikes are formed at the interface where the ambient pressure in the surrounding coolant exceeds the pressure inside the bubble. Thus, if the spike is already formed and the reflected pressure is very strong such that the local pressure gradient is in the direction from the coolant to the bubble, the spike might grow and cause instability of the fluid flow, as described by Taylor[5]. (c) in the case of shallow coolant excursion, the gas bubble expands extremely fast. This bubble first migrates upward and then comes in contact with the vessel cover. Finally, it forces the impinging coolant to fall back in the coolant region. There is no jet-like spike occurring at the top surface of the gas bubble.

Total force acting on the vessel cover for both cases studied is exhibited in Fig. 14. The pulses due to sodium slug impact are clearly indicated in the graphs. It should be mentioned that in the case of shallow coolant excursion, the force generated by the slug impact is insignificant. However, due to the direct contact of the gas bubble with the vessel cover, the thermal loading may be of significant importance in the reactor design.

To further validate the code prediction on bubble dynamics, the code was used to correlate the bubble motion of an ANL experiment performed for studying the motion of an HCDA bubble. The test apparatus used in the experiment is shown in Fig. 15. The test vessel, containing a 12-in.-high column of water, was initially closed and covered by a thin diaphragm membrane. The diaphragm was broken by the diaphragm break rod which falls on signal under the effect of gravity. This permits the high-pressure air to expand rapidly into the liquid region. The behavior of the expanding bubble was recorded photographically and a pressure gauge is set up at Location A to obtain the pressure history.

Figure 16 presents the bubble configurations and fluid motions of the ICECO results at seven different instants. These configurations show how the free surface moves, and how the bubble expands and contracts. First, the gas bubble expanded spherically and reached its maximum radius at approximately 22 msec. Then a dent was generated at the bubble vertex and the bubble became toroidal in shape. The dent at the bubble vertex was caused by the fluid hydrodynamic pressure, which exceeded the bubble internal pressure and thus caused the reversal of the fluid motion. Because of the further depression of the dent, the gas bubble became unstable and collapsed shortly after 41.5 msec, at which time the computation was ceased.

Experimentally recorded bubble motions at seven different instants are exhibited in Fig. 17. These configurations show how the bubble expands and contracts during the course of motion. The maximum bubble also occurred at 22 msec. To compare the results, the positions of the bubble boundary at the symmetry axis obtained by the ICECO analysis are also shown in this figure. The good agreement of the ICECO results with experimental data indicates that ICECO is a promising tool for investigating bubble motion during an HCDA.

3.3 Response of a Piping Loop

The piping loop consists of six elastic-plastic pipes and five rigid elbows connected in series, as shown in Fig. 18. Table I gives the dimensions of the components of the loop.

The inlet to the loop is subject to a 50-bar step pressure pulse; the outlet is subject to a 25-bar step pressure pulse; both are of 7 msec duration. The pipe walls are assumed made of elastic-plastic Nickel-200 whose stress-strain curve is approximated by a bilinear curve with a yield stress of 1207 bars. Meanwhile, the elbow walls are considered as rigid.

Figure 19 gives the computed pressure traces at various locations in the loop. In general, the pressure pulses at locations away from the pressure source are reduced by the wall deformation if the pressure source is greater than the yield stress of the pipe. However, this is no longer true in the case of a loop subjected to two pulses at both ends. As can be seen from this sample problem, a second pulse is formed when the two pulses meet at the middle of the loop near Location 5. Further

pipe wall deformation and interaction with the applied pulses as the reflected wave moves toward the ends causes the pulse in pipe 3 to increase to 54 bars.

This can be further illustrated by the deformation of pipe 4 at various times, given in Fig. 20. It shows that at $t = 2$ msec, the two pulses meet near node 7, at Location 5, causing immediate deformation in that vicinity, which is represented by the bulge shown. Soon after, the bulge spreads in both directions, indicating the propagation of the pressure wave is moving toward the middle of the pipe. This new pressure wave is the result of the interaction between the reflected pressure wave and the applied pulse.

The results also show that plastic deformation occurs everywhere in the loop except at node 13, where the deformation is elastic. As expected, the pressure near the outer wall of the elbow was found to become higher than the pressure near the inner wall of the elbow, because of the effects of the centrifugal forces.

4. Concluding Remarks

It has been demonstrated that the implicit Eulerian code is capable of analyzing various excursion phenomena in fast reactor containments of LMFBRs following an HCDA. The results of the three sample problems indicate that the Eulerian code can give reasonable accurate results for problems involving large material distortions, and more importantly, it can provide stable solutions when the time of numerical computation is greatly extended. The good agreement of the code predictions with experimental data further indicates that ICECO is a promising tool for investigating bubble motion during an HCDA.

The application of the Eulerian code is not limited to the primary containment and piping loops. It can be applied to other areas of reactor problems as well. In fact, the ICECO code has been modified and utilized in some other calculations involving neutronics[6] and heat transfer[7].

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TABLE I. Dimensions of Loop Components*

Pipe, 3" OD x 40 mil		Elbow		
No.	Length, in.	No.	Total Angle, degree	Radius of Curvature, in.
1	7.5	1	90	4.5
2	12	2	90	4.5
3	18	3	90	4.5
4	54	4	180	4.5
5	24	5	90	4.5
6	12			

* 1/10th-scaled model.

Figure Captions

- Fig. 1. Configuration of the Moving Wall and Boundary Cell.
- Fig. 2. Marker-particle Configurations (for opening in containment wall).
- Fig. 3. Relation between Regular and Irregular Cells.
- Fig. 4. Subcells for Penetration - Opening Calculation.
- Fig. 5. Penetration Openings on the Cover Head.
- Fig. 6. Mathematical Model of the Elbow and the Eulerian Mesh.
- Fig. 7. Initial Configuration for the Slug Impact and Sodium Spillage Analysis.
- Fig. 8. Plug-Force Histories.
- Fig. 9. Pressure Histories at Zone (6,14).
- Fig. 10. Reactor Configurations and Coolant Motions at Various Times.
- Fig. 11. Initial Configurations for the Analysis of Dynamics of HCDA Bubbles in Primary Containment.
- Fig. 12. Bubble Configurations at Three Distinct Instants (relatively deep excursion).
- Fig. 13. Bubble Configurations at Three Distinct Instants (shallow coolant excursion).
- Fig. 14. Total Forces on the Vessel Cover as a Function of Time.
- Fig. 15. Simplified Test Apparatus for Bubble Motion.
- Fig. 16. Bubble Configurations and Fluid Motions at Seven Distinct Instants.
- Fig. 17. Experimental Bubble Configurations at Seven Different Instants.
- Fig. 18. Mathematical Model of the Pipe-Elbow Loop.
- Fig. 19. Pressure Histories at Various Locations in the Pipe-Elbow Loop.
- Fig. 20. Wall Configuration of Pipe 4.

Fig. 1

Fig. 2

Fig. 3

Fig 7

Fig. 5

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Fig. 2. Model of Elbow.

Fig. 6

Fig. 7

Fig. 1

Fig. 1

(a) Time = 7.25 msec

(b) 16.0 msec

(c) 24.75 msec

Fig 11

$t = 15.20 \text{ msec}$

$t = 21.80 \text{ msec}$

$t = 33.80 \text{ msec}$

Fig. 12

TIME, msec 14.40

23.40

32.40

Fig. 3

Fig. 17

Fig. 5

Fig. 17

Fig. 17

Fig. 9. Pressure Histories at Various Locations in the Pipe-Elbow Loop.

Fig. 20