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MARTINS: A Foam/Film Flow Model for Molten Material Relocation in HWRs with U-Al-Fueled Multi-Tube Assemblies

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I. INTRODUCTION

Some special purpose heavy-water reactors (HWR) are made of assemblies consisting of a number of coaxial aluminum-clad U-Al alloy fuel tubes and an outer Al sleeve surrounding the fuel tubes. The heavy water coolant flows in the annular gaps between the circular tubes. Analysis of severe accidents in such reactors requires a model for predicting the behavior of the fuel tubes as they melt and disrupt. This paper describes a detailed, mechanistic model for fuel tube heatup, melting, freezing, and molten material relocation, called MARTINS (Melting and Relocation of Tubes in Nuclear Subassembly). The paper presents the modeling of the phenomena in MARTINS, and an application of the model to analysis of a reactivity insertion accident. Some models[1,2] are being developed to compute gradual downward relocation of molten material at decay-heat power levels via candling along intact tubes, neglecting coolant vapor hydrodynamic forces on molten material. These models are inadequate for high power accident sequences involving significant hydrodynamic forces. These forces are included in MARTINS.

II. PHENOMENOLOGICAL DESCRIPTION OF THE MODEL

Beginning with the disruption (i.e., formation of a porous molten fuel-cladding mixture after attaining a specified melt fraction) of a tube segment in an assembly, the MARTINS model calculates the transient (a) axial distribution of mass, Al weight fraction, temperature, velocity, porosity and fission gas content of the molten and frozen materials (U-Al mixtures) in coolant channels, (b) disruption pattern of the tubes of the assembly, (c) coolant channel flow areas left open by the molten and frozen U-Al mixtures, and (d) mass and temperature of the mixture ejected above and below the core. The calculation accounts for the change in intra-assembly radial power distribution shape due to the shielding of an inner tube by the outer tubes remaining intact as well as by the U-Al mixtures located in the outer rings of the assembly.

Three possible regimes for the molten material flow inside the outer sleeve of an assembly have been identified: (1) film flow, (2) foam flow, and (3) droplet/particulate flow. The MARTINS model addresses only the foam and the film flow regimes (see Fig. 1), and is applicable to protected and low-power unprotected voided-coolant accident sequences, up to the time of sleeve failure. The droplet/particulate flow regime is addressed by the DIANA model[3] that is applicable to high-power unprotected accident sequences, possibly with some water present.

In MARTINS, when an axial segment of a fuel tube heats up and each of the inner cladding, meat and outer cladding attains a specified melt fraction, the segment is assumed to disrupt, i.e., to form a foam of molten meat-cladding mixture. If a frozen meat-cladding mixture is adhering to the inner or outer surface of the tube segment, each frozen mixture is also required to satisfy the same melt fraction criterion for disruption. The model calculates the progress of segment-wise disruption of all the fuel tubes until the outer sleeve heats up and disrupts. The model keeps track of the composition of the molten U-Al mixture formed after disruption (1) to determine the solidus and liquidus temperatures and other thermal properties for use in freezing and remelting calculations, and (2) to provide reactor composition for computing power distribution using space-time neutronics. The molten

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mixture foam formed after disruption (1) may contain enough fission gas to cause the foam to expand to fill the entire cross-sectional area of the two surrounding coolant channels, and subsequently the foam will move axially as a slug, resulting in the foam flow regime, or (2) may contain a smaller amount of fission gas compared to case 1 and therefore the molten mixture will not expand enough to fill the entire cross-sectional area of the two surrounding coolant channels but will move axially as a porous molten mixture film on the inner and outer surfaces of the disrupted tube, resulting in the film flow regime (see Fig. 1).

The initial axial length of the foam or film formed after disruption is assumed to remain equal to the original tube segment length. The porosity of the molten mixture, in the foam flow regime, is determined in the model from the volume and mass of the foam, and the theoretical density of the U-Al mixture forming the molten foam. The composition dependence of the U-Al mixture theoretical density is accounted. The porosity at the time of formation of the molten mixture, in the film flow regime, is input to the model. The temporal variation of porosity in each flow regime is determined based on the equilibrium of the internal gas pressure of the molten mixture and the local pressure in the coolant channel along with the effect of surface tension. The number of gas bubbles in the molten mixture and the amount of fission gas in the fuel meat determine the gas pressure inside the bubbles.

The MARTINS model computes heat transfer in the radial direction through all the layers of coolant, cladding, fuel meat, molten U-Al mixture and frozen mixture in the disrupted region. The reduction in the thermal conductivity of the molten foam or film is evaluated using the above porosity. The freezing and remelting calculations are performed based on a method used in the LEVITATE fuel motion module[4] of the SAS4A liquid-metal reactor code. The solidus and liquidus temperatures and enthalpies used in the freezing and remelting calculations in an axial segment are evaluated based on the local compositions of the molten and frozen U-Al mixtures in the axial segment. The frozen mixture is assumed to require an intact tube segment for its deposition and support. In the foam flow regime, the frozen mixture forms two frozen layers, one on each surrounding intact tube. In the film flow regime, the frozen mixture is deposited on the tube supporting the film. As molten mixtures of different compositions are deposited and the frozen layer thickness increases, the model keeps track of only the average composition of the frozen layer in an axial segment. It is this average composition which is used in the evaluation of the solidus and liquidus temperatures and enthalpies of the frozen mixture.

The axial motion of the molten U-Al mixture, in both foam and film flow regimes, is computed using a multiple slug Lagrangian approach. Contiguous tube axial segments disrupting simultaneously form different foam or film slugs (on each side of the disrupting tube), each being of uniform composition and porosity. In addition, in the film flow regime, the cross-sectional area of the film slug is also assumed to be uniform over its length. If another tube segment disrupts later, and the segment is located between the extremities of an already existing slug, then that segment is combined with the existing slug. The velocity and position of the slug center of mass is calculated using a momentum equation for each slug. Each slug is characterized in the model by (a) the mass and Al weight fraction of molten U-Al mixture in the slug, (b) lower and upper end positions, and (c) fission gas mass, porosity and number of gas bubbles. Each foam or film slug is assumed to expand or contract during axial motion, due to the equilibration of the pressure of entrained gases in the slug and the local pressure in the coolant channel. The total axial motion is computed in two steps. First, an axial translation of the slug is computed under the influence of (a) the coolant pressure gradient, (b) the gravity, (c) the friction on the tube wall, and (d) in the case of film flow regime, also the film-coolant interfacial friction. Then an expansion of the slug length due to the pressure of the entrained gases is computed keeping the slug center of mass fixed. For radial heat transfer calculation, the above multiple slug characterization of the molten mixture is mapped onto the heat transfer axial mesh.

The frictional pressure drop on the tube wall is computed in the model

based on the thickness of slip layer.[5] The molten mixture film-coolant (vapor) interfacial friction is computed based on the Wallis correlations for the interfacial friction factor for wavy annular flow, and the onset of disturbance waves on the interface, i.e., flooding.[6] The apparent viscosity of the molten mixture foam, required in the calculation of the film-coolant interfacial friction, is evaluated using the Hirasaki-Lawson equation.[7]

III. MATHEMATICAL DESCRIPTION OF THE MODEL

A. Radial Node Structure During Tube Disruption

The number and material of the nodes used in the radial temperature profile calculation at an axial level in the assembly changes during the transient. This change is accounted for in the model by assigning two types of indices to all the radial nodes ever allowed to be present in the calculation: (1) a permanent identification index, and (2) a sequential finite difference equation index to the nodes actually present at the current transient time, based on the radial geometrical location of the node. All of the nodes actually absent are assigned an equation index of zero, and no finite difference equation is set up for these nodes. The model assumes one radial node in the coolant, two nodes in the inner cladding, three nodes in the meat and two nodes in the outer cladding. The outer sleeve is modeled using two radial nodes. The model allows one radial node in each molten or frozen U-Al mixture layer. There are altogether 67 possible nodes in a six-channel assembly.

B. Molten U-Al Mixture Motion

The axial motion of the molten U-Al mixture, in both foam and film flow regimes, is computed using a multiple slug one-dimensional Lagrangian method. Figure 2 shows a single molten mixture slug in the foam flow regime, with the slug extending over more than one heat transfer axial segments. A number of such foam slugs (or film slugs in the case of film flow regime) can be present in a coolant channel at a time during the disruption of an assembly. The theoretical density depends upon the mixture composition. Since the composition and porosity are assumed to be uniform over the slug length, therefore, the slug density is also uniform over its length. Based on Fig. 2, the continuity of molten mixture mass flow rate gives the following relations.

$$\rho A_1 V_1 = \rho A_2 V_2 = \rho A_3 V_3 = W \qquad (1)$$

where

ρ = porous molten mixture density,

A_i = cross sectional area of the slug in different heat transfer axial segments,

V_i = molten mixture velocity in different axial segments, and

W = molten mixture mass flow rate for the slug.

The rate of change of momentum of the slug equals the resultant of the external forces acting on the slug (see Fig. 2).

$$\frac{d}{dt}\left(W\Sigma_i \frac{L_i}{A_i}\right) = (p_1 - p_4) - \rho g L - \Delta p_f + \Delta p_{int} \qquad (2)$$

where

L_i = length of the slug portion located in the axial segment i,

(p_1-p_4) = coolant pressure drop over the whole slug length,

g = acceleration due to gravity,

L = length of the slug,

Δp_f = frictional pressure drop for the whole slug, and

Δp_{int} = pressure drop due to film-coolant interfacial shear stress.

The interfacial shear stress term in Eq. (2) is good only for film flow regime. The computational steps used for the solution of Eq. (2) are: (1) Evaluate the right-hand side, S_r, of Eq. (2). (2) Evaluate $(\Sigma L_i/A_i)_{old}$, the inertial loss coefficient $\Sigma L_i/A_i$ at time t, the beginning of the time step. (3) Evaluate W', an estimate of $W(t+\Delta t)$, using Eq. 2.

$$W' = W(t) + S_r \Delta t / (\sum_i L_i/A_i)_{old} \quad (3)$$

(4) Find the axial movement of the slug center of mass given by $V_g \Delta t$ where the velocity of the slug center of mass V_g, equals the estimated slug momentum divided by the slug mass, M_g.

$$V_g = LW'/M_g \quad (4)$$

(5) Place the slug in the estimated new position by placing half of the slug mass above and half below the estimated position of center of mass. (6) Evaluate $\sum_i L_i/A_i)_{est}$, the inertial loss coefficient in the estimated new position, and then the final mass flow rate $W(t+\Delta t)$ using Eq. (2).

$$W(t+\Delta t) = W(t) + \frac{S_r \Delta t}{0.5[(\sum_i L_i/A_i)_{old} + (\sum_i L_i/A_i)_{est}]} \quad (5)$$

C. Pressure Drop Due to Tube Wall Friction

The frictional pressure drop, $\Delta p_{f,i}$, for the foam or film slug portion located in a heat transfer axial segment i is computed based on the thickness of slip layer.[5] The slip layer is a liquid film (of liquid coming from the foam) which lubricates the foam at the walls, and the pressure drop required to make foam flow in a pipe or an annulus is primarily determined by the thickness of the slip layer rather than directly by the properties of the foam itself.[5] In the film flow regime, the mobile mixture in the film is also generally highly porous, and is therefore treated like foam in the calculation of the frictional pressure drop. For the sake of clarity, the subscript i indicating the axial segment will be dropped in this section. The slip layer thickness is given by[5]

$$\delta_w = 2r_c \left(\frac{3\mu V}{\sigma}\right)^{2/3} \quad (6)$$

where μ and σ are viscosity and surface tension of the liquid in the foam, V is the velocity of the slug portion located in the axial segment, and r_c is the radius of curvature of the gas-liquid interface in the foam. The liquid refers to the molten U-Al mixture, and the gas refers to the entrained fission gas in the bubbles. The radius of curvature r_c is given by[7]

$$r_c = \begin{cases} r_b & \text{if } R \geq r_b\sqrt{2} \text{ and } P \leq 0.743 \\ 1.788 r_b (1-P)^{1/2}/P^{1/3} & \text{if } R \geq r_b\sqrt{2} \text{ and } P > 0.743 \\ \text{Min}\left[R, r_b, r_b\left\{\frac{1.553(1-P)r_b}{PR}\right\}^{1/2}\right] & \text{if } R < r_b\sqrt{2} \end{cases} \quad (7)$$

where r_b is equivalent radius of the bubbles in the foam, P is porosity of the foam, and R is half of the effective-laminar-diameter, i.e., equals 0.334 times the hydraulic diameter D_{hm} for mobile mixture flow.[8] The wall frictional shear stress τ is related to the slip layer thickness δ_w.

$$\tau = \frac{\mu V}{\delta_w} \quad (8)$$

Using the value of τ from Eq. (8), the frictional pressure drop, Δp_f, for the slug portion located in a heat transfer axial segment can be written as

$$\Delta p_f = \frac{4L\mu V}{D_{h,m}\delta_w} \quad (9)$$

D. Film-Coolant Interfacial Friction

The molten mixture film-coolant (vapor) interfacial shear stress expressed as a pressure drop, $\Delta p_{int,i}$, for the film slug portion located in an axial segment i is computed based on the Wallis correlations for the interfacial friction factor for wavy annular flow, and the onset of disturbance waves on the interface, i.e., flooding.[6] The film-coolant interface remains smooth if the flooding criterion is not satisfied, and the interfacial friction factor, f_i equals the Darcy friction factor f_{sp}, for

smooth pipe wall.[8] If the coolant (vapor) velocity is high enough to satisfy the flooding criterion, then large waves appear on the film-coolant interface, and the interfacial friction factor increases to the value given by the Wallis correlation for wavy annular flow.

$$f_i = \begin{cases} f_{sp} = 1.02(\log Re,c)^{-2.5} \\ \quad \text{if no flooding} \\ f_{sp}(1 + 300\ \delta/D_h) \\ \quad \text{if flooding} \end{cases} \tag{10}$$

where $R_{e,c}$ is the Reynolds number for the coolant flow and is evaluated using the relative coolant velocity $|V_c-V|$ and the hydraulic diameter $2.|R_{int} - R_{far}|$ based on the geometry of a film slug portion shown in Fig. 3. The subscript i indicating the axial segment has been dropped in this section for the sake of clarity. δ is molten mixture film thickness, and D_h is the hydraulic diameter for the coolant and the molten mixture film flow given by $2.|R_{sup} - R_{far}|$.

The Wallis correlation for the onset of disturbance waves on the coolant-film interface can be written as follows.[6]

$$\sqrt{j_c^*} + m\sqrt{j_f^*} = 0.94 \tag{11}$$

$$j_c^* = \alpha|V_c|\left(\frac{\rho_c}{gD_h|\rho - \rho_c|}\right)^{1/2} \tag{12}$$

$$j_f^* = (1-\alpha)|V|\left(\frac{\rho}{gD_h|\rho - \rho_c|}\right)^{1/2} \tag{13}$$

$$m = \begin{cases} 5.6/N_f^{1/2} & \text{if } N_f \le 4, \\ 3.3168 - 0.3728\ \ell n\ N_f \\ \quad \text{if } 4 < N_f < 500, \\ 1 \quad \text{if } N_f \ge 500 \end{cases} \tag{14}$$

$$N_f = \frac{\rho D_h}{\mu_{app}}\left(\frac{gD_h|\rho - \rho_c|}{\rho}\right)^{1/2} \tag{15}$$

where

α = coolant volume fraction in the film-coolant flow,
ρ_c = coolant density,
μ_{app} = apparent viscosity of the molten mixture foam in the film.

Using the interfacial friction factor obtained from Eq. (10), the interfacial shear stress, τ_i, is expressed as a pressure drop, Δp_{int}, for the film slug portion located in an axial segment, using the following equations (see Fig. 3).

$$\tau_i = f_i\rho_c|V_c - V|.(V_c - V)/8 \tag{16}$$

$$\Delta p_{int} = \frac{2R_{int}\ L\ \tau_i}{(R_{sup}^2 - R_{int}^2)} \tag{17}$$

E. Apparent Viscosity of Foam

The apparent viscosity, μ_{app}, of the molten mixture foam is computed based on the following Hirasaki-Lawson equation[7] which accounts for the dependence of apparent viscosity on the foam texture (measured by the average equivalent radius of the bubbles), the hydraulic diameter, foam velocity and porosity.

$$\frac{\mu_{app}}{\mu} = n_L L_S + 0.85\ n_L\ \frac{(r_c^2 + R^2)}{r_c(3\mu V/\sigma)^{1/3}} + \frac{n_L R(\beta/r_c)^{1/2}}{(3\mu V/\sigma)^{1/3}} \cdot \tanh\left(\frac{L_b/r_c}{(\beta/r_c)^{1/2}(3\mu V/\sigma)^{1/3}}\right) \tag{18}$$

$$n_L = \begin{cases} 1.5\ P/r_b & \text{if } R \ge r_b\sqrt{2} \\ 0.75\ PR^2/r_b^3 & \text{if } R < r_b\sqrt{2} \end{cases} \tag{19}$$

$$L_s = \text{Max}\left(0,\ \frac{1-P}{n_L} - \frac{2R}{3}\right) \tag{20}$$

$$L_b = \begin{cases} P/n_L - 4R/3 & \text{if } L_s \neq 0 \\ P/n_L - 2r_c + (4-\pi)r_c^2/R & \\ \quad \text{if } L_s = 0 & \end{cases} \qquad (21)$$

where

μ = viscosity of the liquid, i.e., 100% dense molten mixture in the foam,

n_L = number of equivalent lamellae per unit length of the coolant channel,

L_s = length of the liquid, i.e., 100% dense molten mixture, between two consecutive bubbles in the foam,

β = an empirical parameter experimentally determined to be 0.05 m, and

L_b = length of a bubble in the foam.

F. Post-Disruption Intra-Assembly Radial Power Distribution

The DIF3D nodal hexagonal-z reactor kinetics[9] used to compute reactor power distribution homogenizes all materials located, and computes the total power produced, in an axial segment of a fuel assembly. It does not compute the distribution of this power into the intact fuel tubes and the meat-cladding mixtures formed, in the MARTINS fuel motion model, after tube disruption. The ring-by-ring intra-assembly distribution of this power after tube disruption is very different from the distribution before disruption because a disrupted ring (a coolant subchannel plus the surrounding tube) segment not containing any U-Al mixture will have zero power. The ring-by-ring distribution of the power is very important because it is the driving cause of all thermal-hydraulic, material melting and relocation phenomena in each ring. The approximate method used for distributing the power consists of two parts: (1) calculation of the relative values of ring-by-ring power per unit uranium mass and power per unit mass of neutron-capturing material, if any, in a given assembly axial segment, and (2) normalization of these relative values such that the total power of all rings (tubes and U-Al mixtures) equals the DIF3D-computed power of the assembly axial segment.

The calculation of the relative values of ring-by-ring power per unit mass accounts for the shielding of an inner tube by the outer tubes remaining intact in the assembly axial segment as well as by the U-Al mixtures located in the outer rings of the segment. Practically all the moderator lies outside the assembly and, therefore, all the thermal neutron source is outside the assembly. There is a thermal neutron current from the moderator outside the assembly to the tube meats inside the assembly where the thermal neutrons are absorbed. Neglecting the thermal neutron absorption cross sections of water and aluminum compared to those of uranium, the attenuation of thermal neutron flux, ϕ, as the thermal neutrons travel radially inward from the moderator into the tube meats, is calculated using a mass attenuation coefficient for uranium, μ_u, and another coefficient for the neutron-capturing material, μ_c.

$$\phi = \phi_o \exp(-\mu_u x - \mu_c y) \qquad (22)$$

where ϕ_o is thermal neutron flux in the moderator outside the assembly, x is mass thickness of uranium between the radial position and the sleeve, kg/m^2, and y is mass thickness of the capturing material between the radial position and the sleeve, kg/m^2. Assuming that all the energy generated in uranium is due to thermal neutron fission, and all the energy generated in the capturing material is due to thermal neutron capture, the powers per unit mass of uranium and capturing material, q and q_c, are given by the following equations:

$$q = F_1 \exp(-\mu_u x - \mu_c y) \qquad (23)$$

$$q_c = \frac{F_2}{F_1} q \qquad (24)$$

$$F_1 = \gamma \sigma_f A \phi_o / A_u \qquad (25)$$

$$F_2 = \gamma_c \sigma_c A \phi_o / A_c \quad (26)$$

where σ_f is microscopic fission cross section of uranium, A_u is atomic weight of uranium, γ is energy per fission, σ_c is microscopic capture cross section of the capturing material, A_c is its atomic weight, γ_c is energy per capture, and A is Avogadro's number.

The relative values of ring-by-ring powers per unit mass can be found by arbitrarily assuming F_1 to be 1.0. The values of other parameters in Eqs. (23) and (24), i.e., μ_u, μ_c, and F_2/F_1, are determined by matching the fuel tube powers obtained from these equations with the input data (for fuel tube powers) for the intact assembly in steady state. During transient after tube disruption, the relative values of the powers per unit mass in the remaining intact tubes and the U-Al mixtures present in coolant channels are determined using the same values of the above parameters.

IV. APPLICATION TO A REACTIVITY INSERTION ACCIDENT (RIA) ANALYSIS

The film flow regime of the MARTINS model was used to calculate molten material relocation during an unprotected RIA caused by a reactivity insertion rate of 0.01$/sec to a maximum of 0.2$ in a 2500 MWt HWR design. The coolant inlet temperature was held constant at 322K throughout the 40-second transient. A post-disruption coolant vapor velocity of 15 m/sec at coolant channel inlet was specified. The reactor power rises to 2.25 times the nominal power. Only the outermost fuel tube disrupts during this transient. The disruption begins at time 27.586 sec after the beginning of reactivity insertion, and the whole tube is disrupted before the time 32.0 sec. Figure 4 compares the mixture mass ejected above the core calculated for this transient using two different time steps in the model. Further applications of the model are described in Ref. 10.

V. CONCLUDING REMARKS

A mechanistic model for molten core material relocation in an HWR assembly has been developed. One of its separate-effect models, i.e., the molten U-Al mixture foam apparent viscosity model has been validated by comparison with experimental data. Other aspects of the model remain to be validated.

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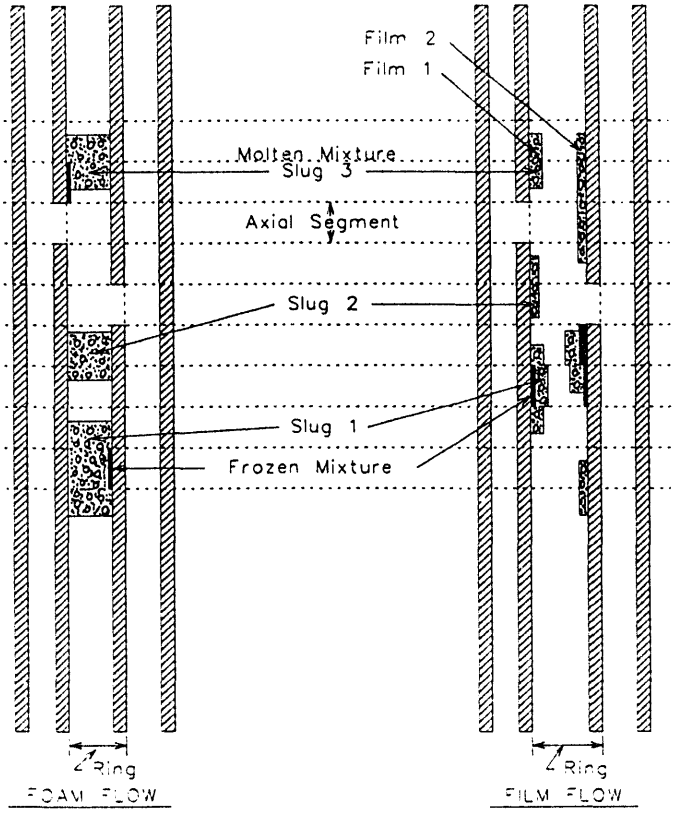

Fig. 1. Multiple Mobile Slugs in a Typical Ring.

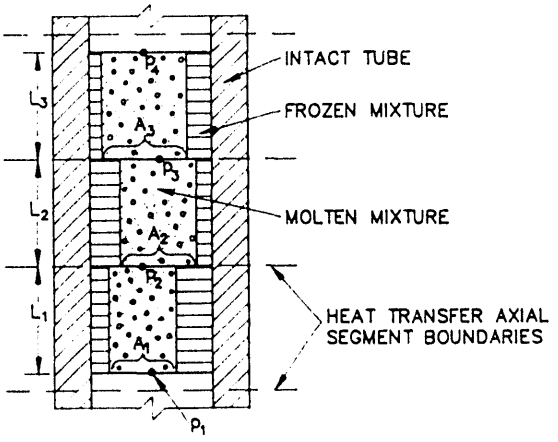

Fig. 2. A Mobile Foam Slug in a Typical Ring.

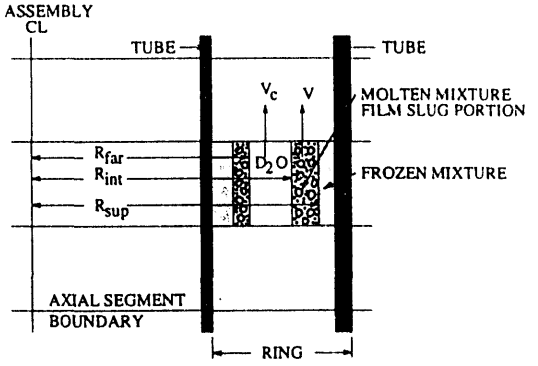

Fig. 3. A Mobile Film Slug Portion Located in an Axial Segment.

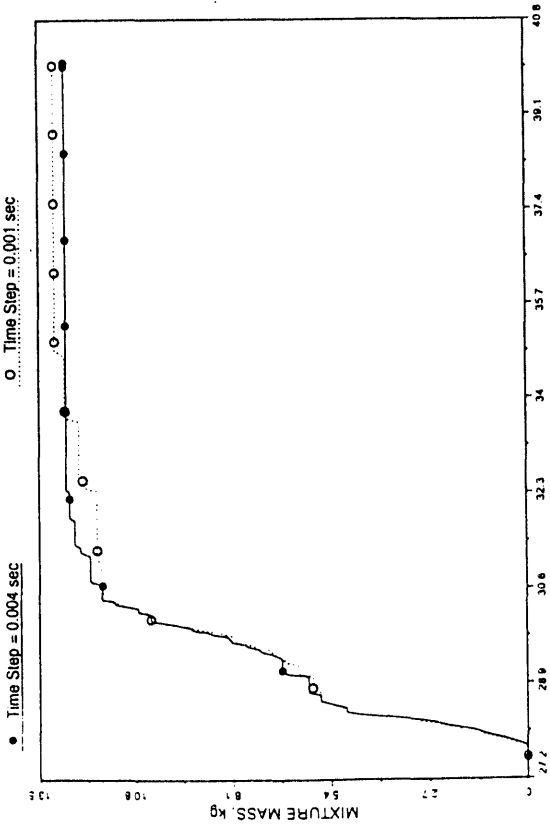

Fig. 4. Mixture Mass Ejected Above Core in an Assembly During a 0.01$/sec RIA.

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