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MOLTEN FUEL MOTION DURING A FAST-REACTOR OVERPOWER TRANSIENT

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ABSTRACT

Mechanistic models for postfailure fuel behavior during hypothetical transient overpower accidents are currently being developed for incorporation into the MELT accident analysis code. A new model for the fuel-coolant interaction and for the motion of fuel in the coolant channel has been developed and incorporated into the MELT-III code. A major limitation of the mechanistic fuel motion model is its dependence on the uniform interaction region of MELT-III. Consequently, a parallel effort is currently in progress to incorporate a non-uniform interaction region into the MELT code. Combination of the fuel motion and the non-uniform interaction region models will provide the framework for development of a mechanistic fuel plateout/blockage model for transient overpower accidents.

INTRODUCTION

Fuel expulsion from the reactor core has been shown to be a potential neutronic shutdown mechanism during a hypothetical unprotected transient overpower (TOP) accident in a LMFBR system [1,2,3]. In the analysis of the TOP accident, the trend has been to develop more mechanistic models to predict the post-failure motion of molten fuel both inside the fuel pin and in the coolant channel. In order to assess the importance of these modeling improvements, it is necessary to integrate the new models into consistent accident analysis codes. The purpose of this paper is to describe the fuel motion models being incorporated into the MELT accident analysis code [4], which is being used to analyze the TOP accident in the FFTF reactor.

The initial MELT code models for characterizing internal fuel motion inside the fuel pin and external fuel motion in the coolant channel were simple, parametric models to assess the reactivity consequences of assumed fuel distributions. More recently, detailed mechanistic models for internal and external fuel motion have been under development for incorporation into the MELT code.

For internal fuel motion, the HOTPIM code [5] (Hydrodynamics of Two-Phase Internal Motion) was developed to predict the transient flow of a compressible two-phase mixture of molten fuel and fission gases using the method of

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characteristics. The HOTPIM code was incorporated into the MELT code and calculations were performed [6] to assess the effect of using the more detailed internal fuel motion calculated by HOTPIM with the previous results using the original uniform cavity model, which maximized the rate of fuel ejection from the pin by assuming a uniform pressure and density inside the fuel pin.

For external fuel motion, the original parametric model in MELT did not calculate the motion of fuel in the coolant channel. Rather, it specified the distribution of fuel within the two-phase region. In addition, the conditions inside the two-phase interaction region (pressure, temperature, and density) were assumed to be uniform. Three current modeling activities associated with the MELT code are expected to significantly improve the prediction of external fuel motion: the calculation of fuel motion in the coolant channel, the development of a non-uniform interaction region, and the development of a fuel plateout-ablation-blockage model. Experimental data from in-reactor transient tests in the TREAT facility and out-of-reactor bench tests on specific phenomena will be used in ultimate model verification.

FUEL INTERACTION MODEL

Heat Transfer from Fuel to Coolant

An important part of the TOP analysis is the energy exchange between fuel particles and coolant. Uncertainty in such critical features as particle size, interaction mechanisms, and fuel-coolant mixing limit the degree of sophistication that may be reasonably used in the model.

In the new molten fuel-coolant thermal interaction (MFCI) model, heat transfer from the molten fuel to the sodium is calculated by a heat-transfer-limited process. This is in contrast to the fuel-mixing-limited process in the original MELT-III parametric model. In the new model, spherical fuel particles are assumed and the heat transfer coefficient is calculated by the quasi-steady-state approximation of Cho, Ivins, and Wright [7]. At the present time, the fuel particle size is assumed to be constant because of the lack of quantitative information to develop a consistent fuel fragmentation model.

External Fuel Motion

The new mechanistic fuel motion model calculates the motion of fuel particles based on the forces associated with gravity, buoyancy, and drag from the two-phase mixture of sodium and fission gas. Assuming spherical fuel particles, the momentum equation is given by:

$$\frac{dV_f}{dt} = g\left(1 - \frac{\rho}{\rho_f}\right) - \frac{3}{8}\,\frac{C_D V_f^2\,\rho\,\varepsilon^{-2.7}}{r_f\,\rho_f}$$

The drag coefficient C_D is dependent on the Reynolds number for the fuel particle and is given by standard correlations for spherical particles [8]. The above equation allows for the fact that the drag forces will be higher for more densely packed fuel particles (low values of the non-fuel volume fraction ε). To allow for other effects (e.g., effect of finite flow channel size), a user-input multiplier for the drag coefficient is used.

When the new mechanistic fuel motion model is incorporated into the new hydrodynamic model (a task still in progress), the momentum equation for the fuel particle will also incorporate an additional term corresponding to the pressure gradient. In addition, a term corresponding to the drag force on the fuel particle will be added to the momentum equation for the two-phase sodium-fission gas mixture.

COOLANT HYDRODYNAMIC MODEL

The essence of the coolant hydraulics work is to replace the lumped two-phase model used in earlier versions of MELT-III with a more phenomenological description of the dynamics of the carrier fluid.

The basic assumptions of the new model are:

(1) A homogeneous flow pattern with no slip between components;
(2) The liquid-vapor-gas MFCI mixture is assumed to be always in thermodynamic equilibrium at the vapor saturation state;
(3) The non-condensable gas in the MFCI zone diffuses instantaneously so as to be equi-molarly distributed;
(4) Coolant dynamics are one-dimensional;
(5) The ideal gas law is used along with saturated sodium properties to model the gaseous mixture;
(6) As with MELT-III, a single bubble "zone" in residence in the channel is defined: the identity of single bubbles is lost. This is consistent with the mixing volume usually postulated for the MFCI active region.

The coolant channel is modeled by using finite-difference equations in an Eulerian coordinate system. A compressible fluid is simulated in the two-phase region while the subcooled liquid is presumed incompressible. Thereby, disturbances are propagated through a portion of the channel at the local sonic velocity. The major difficulty with compressible models is numerical stability. That is, to retain numerical stability the time-step size must be on the order of the residence time of a sonic wave in a nodal cell. Henry, et. al., [9] shows that the sonic velocity in a two-phase flow regime may be substantially less than in a pure gaseous domain. Thereby, the two-phase condition permits a larger time step. The finite-difference equations used are cast in a form that enhances local numerical stability. Special numerical procedures are employed to simulate the period of most rapid change occurring at bubble initiation.

Equation-of-State

Thermodynamic sodium data in the subcooled and saturated state, along with the ideal gas law and assumptions on the thermodynamic process followed by the gaseous phase, provide information to define a differentiable equation-of-state. This equation-of-state is a function of coolant enthalpy and pressure. Both sodium (liquid and vapor) and fission gas are components of this "fluid". The fuel particles are not regarded as part of the continuum, but rather serve to reduce the available volume.

Differential Equations

The coolant mixture is described by total balances rather than considering each component separately. The fuel particles are described separately with coupling to the total balances planned via a net drag force and energy exchange terms.

The differential form of the equation-of-state is used to transform the equations-of-motion such that density does not appear in derivatives. (See also the definition of M and E later.) Rather, terms of the form:

$$R_P = \left(\frac{\partial \rho}{\partial p}\right)_H = \text{constant}, \qquad R_H = \left(\frac{\partial \rho}{\partial p}\right)_P = \text{constant},$$

appear as coefficients in the total mass and energy equations.

The mass equations involve a balance between temporal acceleration and convection of mass and mass sources and sinks. The momentum relations involve a balance between temporal acceleration, convection of momentum, and pressure, body, and viscous forces. After coupling the mechanistic fuel motion model to these equations-of-motion, a net drag force term will be included in the momentum equation to account for the sum of all fuel particle forces on the fluid mixture.

The energy equations involve a balance between temporal energy variation, axial convection, energy sources, axial conduction, radial (film) convection, and work due to rapid pressurization. The channel area is considered to be a continuous function of axial position.

The usual finite difference simulation of the above balance relations suffer from the inability to average differentials over the phase interfaces. This is because the coolant density is discontinuous at the interface. To overcome this difficulty, two new variables are introduced,

$$M = G^2/\rho \quad \text{and} \quad E = GH,$$

after the technique previously used by Turner [10]. The gradients in the resulting expressions are of G, P, H, and A; each differential capable of being averaged over a phase boundary. The derivatives of M and E with respect to P and H may be discontinuous, but the truncation error may be reduced by a special approximation of Turner [10].

Finite-Difference Equations

The coolant channel transient hydraulics is described by two sets of equations of motion. One set of equations is largely explicit and one set is largely implicit in nature. Alternating use of each set of equations is made with successive time steps. This two time-step procedure is used so that the finite difference representation of space derivatives, as well as certain other nonlinear terms, are taken as alternating forward and backward in time. Thereby, all terms are either central or averaged in time. This multi-operation technique possesses the stability advantages of the implicit scheme yet tends to center the terms in the nodal mesh, thereby improving accuracy [11].

The finite-difference equations that simulate the mass and the momentum balances for the entire flow field are solved simultaneously. In the subcooled liquid the density is assumed pressure invarient. This serves to decouple the mass and momentum balance equations across phase boundaries. The solution then is found by Gaussian elimination (tridiagonal block of equations) in the two-phase domain, and by a "march-out" technique in the subcooled liquid domain. The energy balance also leads to a system of tri-diagonal equations in the enthalpy variable, but is unaffected by phase boundaries.

Simplified Treatment of Fission Gas

The presence of fission gas within a bubble region greatly complicates the theory associated with both the equation-of-state and the iteration process in MELT. Hence, interaction between fission gas and vapor are neglected in the specification of an equation-of-state. Additionally, the overall equations-of-motion do not predict the distribution of the fission gas within the bubble. The latter is dealt with by artificially specifying the distribution as uniform in molar density throughout the two-phase region. This implies a very large diffusion coefficient for the fission gas.

With the presence of fission gas, the partition of energy permits vapor to exist at a lower enthalpy (nodal cell value) than the single component saturation state. This feature distinguishes the MFCI problem from the pure boiling case, and is a considerable complication in the Eulerian formulation.

PRELIMINARY RESULTS

Calculations have been made to illustrate the trends predicted by the fuel motion model when coupled to the standard MELT-III hydrodynamic model (uniform interaction region). The velocity distribution within the interaction region was obtained by assuming a linear variation between the velocities of the upper and lower liquid slugs. The ultimate objective is to introduce this fuel motion

into the new hydrodynamic model which will feature a non-uniform interaction region.

Figure 1 shows the upper and lower liquid interfaces for coolant voiding following fuel failure. The heat transfer from the molten fuel expelled from the pin to the sodium coolant was calculated assuming a fuel particle radius of 0.02 cm.

Superimposed on the coolant voiding curve is a comparison of the fuel distribution for the two fuel motions models at three different times: 45 msec, 105 msec, and 185 msec after failure. For this case, fuel plateout was assumed to be zero. For the original parametric model, a value of 0.7 for the input parameter SKEW [4] was used to conservatively peak the fuel distribution at the failure location. For the new mechanistic model, the fuel particle radius of 0.02 cm was used. One difference between the two models which is readily apparent is that the parametric model distributes the fuel continuously between the upper and lower liquid interfaces whereas the mechanistic model predicts that the fuel particles cannot keep up with the upper liquid interface because of slip between the fuel particles and the sodium-fission gas mixture. This characteristic results in less calculated upward fuel motion at very early times after the start of fuel expulsion from the pin. At later times, the peak in the distribution of fuel particles moves upward away from the core region, whereas the parametric model continues to force a peak at the failure location. This peak continues at the failure location until fuel expulsion from the pin ceases after several hundred milli-seconds after fuel failure and, at that time, the lower liquid interface is allowed to move away from the core region.

A study has been performed to compare the reactivity feedbacks predicted by two fuel motion models. A simple 2-channel representation of the FFTF beginning-of-cycle-4 core was used, where channel 1 represented 16 fuel subassemblies which fail coherently and channel 2 represented the remainder of the reactor core. The analysis assumed a reactivity ramp rate of 50¢/sec. For both fuel motion models the original parametric fuel plateout model was used assuming a plateout rate of 10.0/sec. (1%/msec).

Figure 2 shows both the reactivity feedback due to fuel motion and the net reactivity for the two fuel motion models. Although the fuel motion reactivity includes both internal (inside the fuel pin) and external (in the coolant channel) fuel motion, the internal fuel motion is about the same in all cases and the differences are due primarily to external fuel motion. For the parametric model, a value of 0.7 for the input parameter SKEW was used to conservatively peak the external fuel distribution at the failure location. When fuel expulsion ceases, the two-phase interaction region and all of the mobile fuel is swept out of the active core region at about 0.5 sec after failure. However, there is very little negative reactivity feedback from the fuel sweepout at 0.5 sec because almost all of the fuel expelled into the coolant channel ($\sim$95%) has been plated out.

For the mechanistic fuel motion model, the nominal drag coefficient for the fuel particles was also reduced by an order of magnitude to conservatively estimate the uncertainty in the drag between the fuel and the sodium/fission gas mixture. As already shown in Figure 1, the mechanistic model predicts less fuel motion than the parametric model at very early times after the start of fuel expulsion, and therefore the negative reactivity feedback is slightly lower than for the parametric model with SKEW = 0.7. At later times, the mechanistic model predicts substantially higher negative reactivity feedback as the fuel moves away from the core region because the parametric model forces the fuel distribution to peak at the failure location. Even when the drag coefficient is reduced by an order of magnitude from the nominal value, the mechanistic model eventually predicts much higher negative reactivity feedback than the parametric model with SKEW = 0.7.

With the simple parametric plateout model, a plateout rate of 1%/msec results in plateout of about 95% of the fuel in the coolant channel at 0.5 sec.

However, the location along the coolant channel at which fuel is plated out depends on the distribution of mobile fuel. Figure 3 shows the distribution of plated-out fuel along the subassembly at 0.5 sec after the start of fuel expulsion. For the parametric model with SKEW = 0.7, most of the fuel plateout occurs at the failure location because the mobile fuel distribution is peaked at this location until almost 0.5 sec. For the mechanistic model, the fuel plateout distribution is much more uniform, with a slight peak one node downstream from the failure location. When the drag coefficient for the fuel particles is reduced by an order of magnitude, the fuel motion is sufficiently retarded to substantially increase the fuel plateout in the region of the failure location when compared to the nominal drag coefficient, but the reduction in coolant flow area is still very low.

The differences in the distribution of plated-out fuel shown in Figure 3 result in the differences in the assymptotic values for the fuel motion reactivity shown in Figure 2. There is less negative reactivity feedback for fuel plated out in the active core region than for fuel plated out further downstream in the fission gas plenum region.

FUTURE WORK

Coupling of the mechanistic fuel motion model to the non-uniform interaction region model is in progress. Refinement of both the fuel motion and coolant hydrodynamic models will be made concurrent with the experimental base.

Development of a mechanistic fuel and clad plateout-ablation-blockage model for inclusion in the MELT code has begun. The hydrodynamic model will be modified to follow temporal changes in flow area resulting from any such plateout.

Notation

C_D = drag coefficient

G = coolant mass flux

g = acceleration of gravity

H = coolant enthalpy

P = static pressure

r_f = radius of fuel particle

t = time

V_f = velocity of fuel particle

ε = non-fuel volume fraction

ρ = coolant density

ρ_f = density of fuel particle

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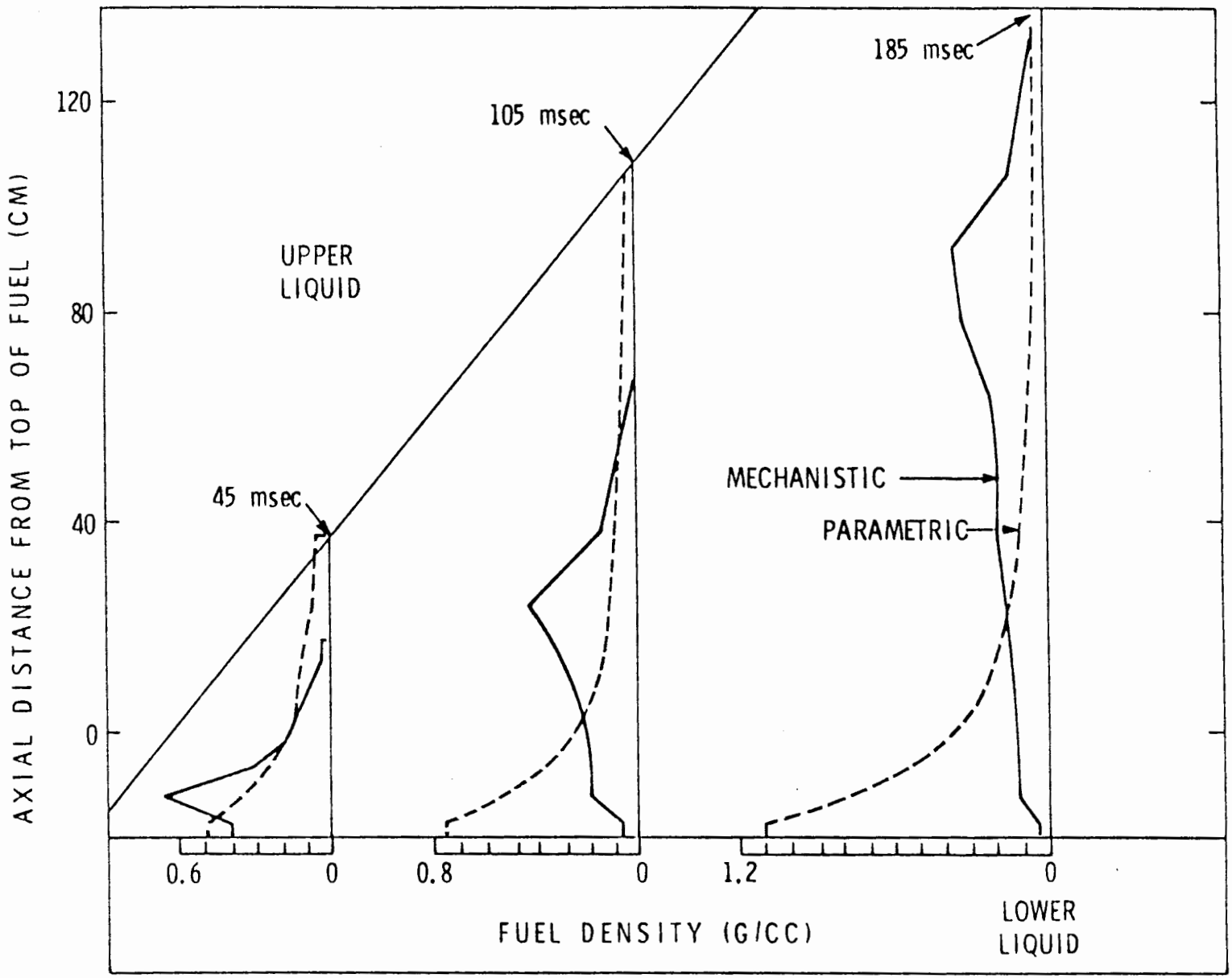

FIGURE 1. FUEL DISTRIBUTIONS FOR MECHANISTIC AND PARAMETRIC FUEL MOTION MODELS

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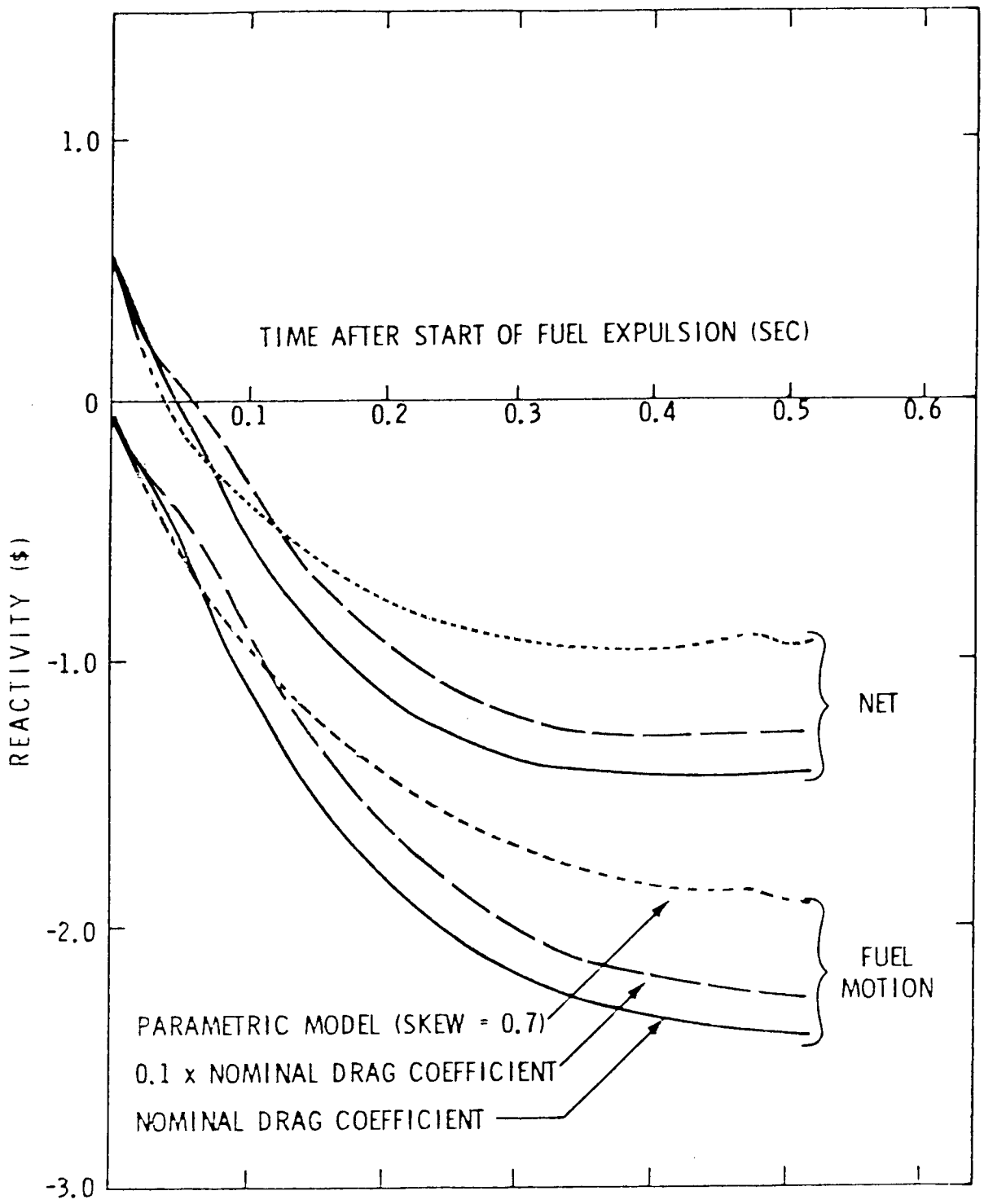

FIGURE 2. REACTIVITIES FOR MECHANISTIC AND PARAMETRIC FUEL MOTION MODELS

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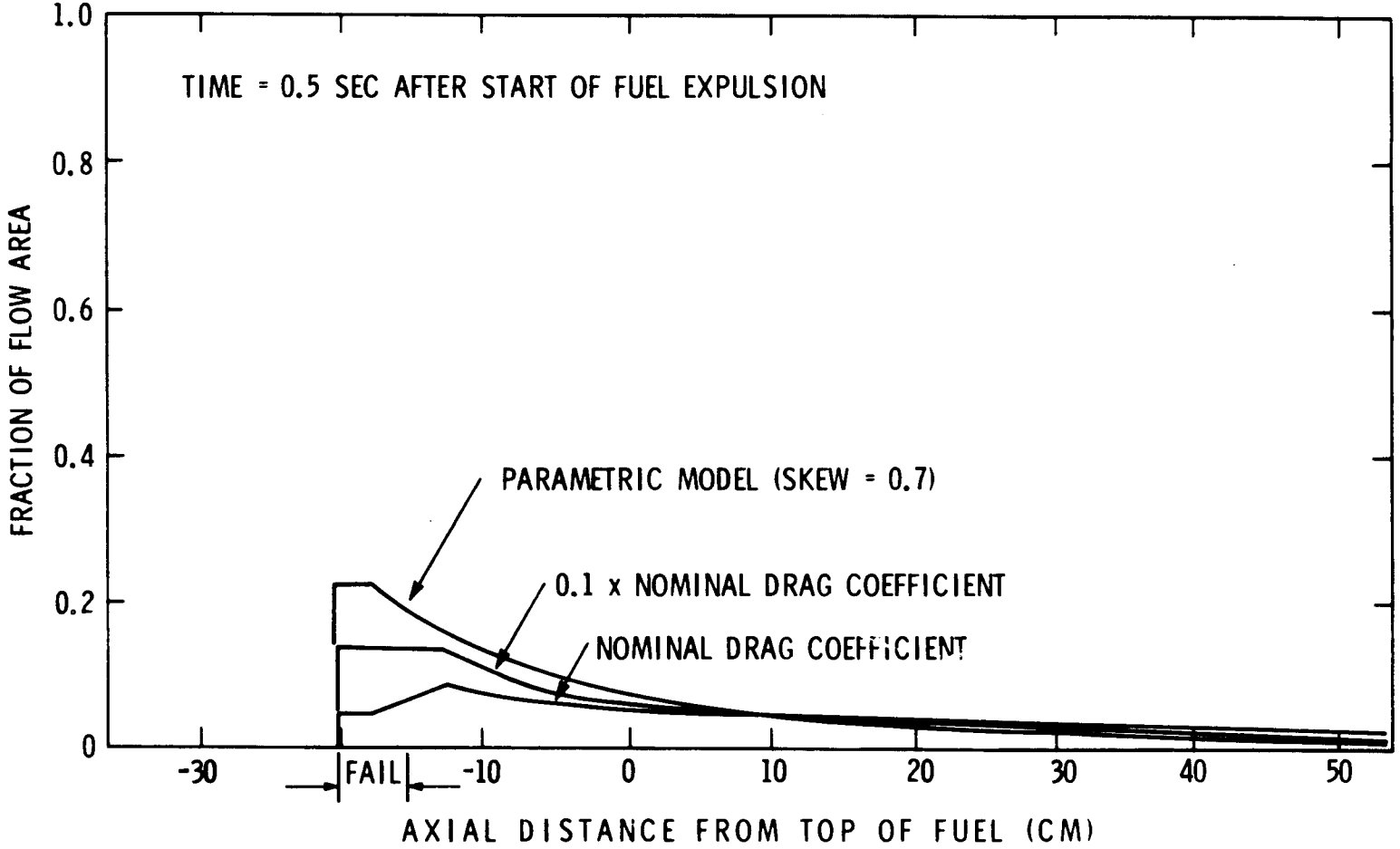

FIGURE 3. DISTRIBUTION OF PLATED-OUT FUEL

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