

A DYNAMIC MODEL FOR FUEL-COOLANT MIXING*

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ABSTRACT

If a complete failure of normal and emergency coolant flow occurs in a light water reactor, fission product decay heat would eventually cause melting of the reactor fuel, and eventual contact with water. This mixing produces steam and hydrogen as the fuel breaks apart. Previous analysis of mixing only looked at the limits to fuel-coolant mixing based on quasi-steady assumptions. This paper describes a dynamic mixing model predicting fuel breakup as it falls through a water pool producing steam and possibly hydrogen. Calculations indicate that in the absence of an energetic fuel-coolant interaction very small amounts of hydrogen are generated during mixing (less than a few percent of metallic fuel reacted).

Introduction

During the past few years the Nuclear Regulatory Commission (NRC) has intensified its evaluation of low probability-high consequence accidents in light water reactors (LWR). The principal purpose of this work is to assess the reactor containment building response following a severe accident where a significant proportion of the core radioactive inventory is released from the fuel rods. This type of accident may be initiated by a number of low probability events which eventually cause a prolonged loss of heat sink to the core and subsequent melting of the core materials. Containment response includes assessment of the accident progression, identification of mechanisms which may threaten containment integrity, and available means to mitigate the consequences associated with these events. These current efforts are an outgrowth of the Reactor Safety Study (RSS), the accident at the Three Mile Island Unit 2 Nuclear Power Station, and the reexamination of the capabilities of present generation LWR's to accommodate the effects of degraded-core and core-melt accidents.

Containment integrity may be threatened by physical processes that involve contact between the overheated and possibly molten core materials (Corium fuel) and other materials present in the containment such as water, steel, or concrete. In this paper consideration is given to fuel-coolant interactions both in-vessel and ex-vessel, under the probable scenario of fuel-coolant contact [1-5]. Specifically, we present a dynamic model for fuel-coolant mixing when Corium fuel pours into a water pool and breaks apart producing steam and hydrogen (if the fuel is metallic), prior to or in the absence of an energetic fuel-coolant interaction.

Past research into fuel-coolant mixing (sometimes called 'premixing') has been directed at predicting the physical limits for which mixing could or could not occur. Fauske [6,7] originally proposed that the fuel-coolant interface temperature upon liquid-liquid contact must exceed the spontaneous nucleation temperature to allow premixing for an energetic FCI. The physical picture was that stable film boiling is established above this limit for a liquid-liquid system and this allows the fuel time to penetrate and mix with the coolant. For the LWR system, the fuel and coolant easily satisfy this first criterion. Cho et al. [8] considered the energy used in fuel-coolant mixing that creates more surface area and overcomes frictional effects. He concluded that frictional effects dominate the energy mixing requirements. For this pair of fuel and coolant, the mixing energy requirements are very small compared to the available energy in the fuel. Fauske and Henry [9,10] subsequently proposed the physical concept that the fuel can break up and premix with the water to a uniform size no smaller than that which would prevent liquid from entering the mixture zone as the steam flows out. The minimum diameter was given by

$$D_{MIN} = \frac{6m_f q''_{DROP}}{\rho_f A_c q''_{CHF}} \quad (1)$$

where q''_{CHF} is the critical heat flux, used as the limit for steam outflow and water inflow.

More recently Corradini [11] suggested that the limit to fuel-coolant mixing was determined by fuel or coolant liquid fluidization; e.g.

$$D_{MIN} = \left[\frac{3}{4} \left(\frac{\alpha_f}{\alpha_v} \right)^2 \left(\frac{6q''_{DROP}}{\rho_v i_{fg}} \right)^2 \left(\frac{C_{DH} C}{g} \right)^2 \left(\frac{\rho_v}{\rho_f} \right) \right]^{1/3} \quad (2)$$

where α_f and α_v are the fuel and vapor volume fraction at any time as the mixture evolves. This limit may never be reached because it takes time for the fuel to dynamically break up to this size, and an energetic fuel-coolant interaction or agglomeration of the fuel on the base may first occur.

This final criterion on the limit to fuel-coolant mixing only makes sense if one knows the dynamic behavior of the fuel-coolant mixture, so that we can calculate the volume fraction of each constituent. Actually the Henry and Fauske criterion for a limit to mixing should also be a dynamic quantity, because the actual area for steam outflow and water inflow would be the time-dependent surface area of the fuel-coolant mixture. Because of these concerns we are developing a dynamic fuel-coolant mixing model for a fuel pouring or injection mode of contact. To our knowledge, no other dynamic

fuel-coolant mixing model has been developed. This model can be used to calculate the rate of steam and hydrogen generation due to oxidation of molten metal [12] and the initial conditions for a fuel-coolant interaction. The mixing model has already been used in a defacto manner to analyze the FITS MD and MDC experimental series [13]. We plan to utilize it in the analysis of the FITS in-chamber experiments (FITSA, FITSB, FITSC and FITSG). This computer model is also being incorporated into the MEDICI computer code to model the fuel discharge phase into the reactor cavity after a reactor vessel failure. In this paper, we describe the current model and present some sample calculations.

Mixing Model Assumptions

The fuel is considered to fall or be injected into a coolant pool (Figure 1), mix with the coolant, and, in the absence of an energetic fuel-coolant interaction, settle on the base as either a molten pool, debris bed or both. The primary assumptions of the present model are:

- (1) The liquids are modelled as incompressible, and the gases and steam vapor are modelled as perfect gases with constant thermophysical and transport properties; these approximate equations of state were considered acceptable for this initial modelling of the phenomena.
- (2) Chemical reactions between molten metals and water are treated sequentially; i.e. first zirconium, if present, is reacted with the water, then chromium, then iron. This assumption reduces the complexity of the chemical reaction equations but still preserves the expected integral behavior.
- (3) The fuel melt is considered to be subdivided into Lagrangian material volumes which fall through the gas atmosphere into the water pool, eventually accumulating in a debris bed, molten pool, or undergoing an energetic fuel-coolant interaction.
- (4) The water pool and gases in the atmosphere and generated by the fuel-coolant interaction are considered to be contained in fixed control volumes; e.g. in the FITS chamber there would be a coolant and gas control volume with no outlet, while in a reactor cavity an expansion path through an access tunnel would be available.
- (5) Within each control volume and material volume the materials are described by lumped parameter mass and energy balance equations.
- (6) We utilized empirical fuel-coolant mixing correlations derived from the FITS MD and MDC test series [13] to describe the dynamic dispersion of the fuel as it falls through the coolant. These correlations replace the detailed multi-dimensional momentum balances one would require to theoretically predict this behavior.
- (7) If an expansion path is available for the fuel-coolant mixture, we model it as a one-dimensional expansion of either liquid coolant or gas flow.

This analysis allows us to calculate the amount of hydrogen and steam produced, the fuel melt characteristic size and temperature, and the heat up of the coolant pool as a function of time.

Fuel Injection and Mixing

The fuel injection is conceptually modelled by breaking up the flowing stream of fuel into a finite number (N) or 'parcels' (Figure 2). A new fuel melt parcel can enter the problem on each major time step with an imposed injection velocity, v_f (e.g. free fall velocity from a FITS melt crucible). The parcel then falls through the atmosphere and water pool at this constant velocity. The fuel is considered to be a homogeneous mixture of melt constituents (e.g. Fe, UO_2 , ZrO_2) with a specified initial diameter, D_{f0} , and temperature, T_f . As time advances, the fuel melt parcels continue to fall through the water pool. Once a new fuel parcel has entered the calculation each of the other $N-1$ parcels are then 'updated'. This is accomplished by moving the fuel melt in parcel N at the bottom of the coolant pool out of the parcel vectors and accumulating its mass and energy into the molten pool or debris bed, while moving the remaining parcels downward as they fall through the water pool. This time step for the fuel injection process is chosen such that a parcel will always have fallen through its fall height to the coolant pool base in less than or equal to N time steps. A fuel parcel may reach the molten fuel pool or the debris bed before this time after release when the pool and debris bed height have risen significantly above the cavity floor.

As each fuel parcel falls into the water pool, it begins to distort in shape and mix while in film boiling. The fuel continues to break apart into smaller pieces with the surrounding water. These smaller molten droplets may subdivide further as the steam produced in film boiling flows out the top of the fuel-coolant mixture and escapes the pool as water flows in from the sides. This mixture grows radially as the fuel now mixed with water and steam continues to fall. This multi-dimensional process is quite difficult to model; therefore we have developed a set of empirical correlations based on the FITS MD and MDC experiments [13] to describe the mixing phenomena in place of detailed momentum balances. We have correlated the growth of the fuel-coolant mixing volume, steam volume in the mixture, and fuel and steam volume fractions to a dimensionless time (Figure 3). Past analysis of these experiments [11] indicated that one reason for the fuel breakup were inertial forces generated by the initial fuel relative velocity and differences in density. As the fuel enters the water its characteristic Weber number (ratio of destabilizing inertial force, $\rho_c v^2$, to stabilizing surface tension force, σ_f/D_{f0}) will be greater than a critical value ($We_{crit} = 7-12$). The mechanism for this breakup is probably due to Rayleigh-Taylor instabilities. Based on this assumption we correlated the data based on two derived dimensionless times [13]

$$t^+ \equiv \frac{v_f t}{D_{f0}} \left(\frac{\rho_c}{\rho_f} \right)^{1/2} \quad (3)$$

and

$$t^* \equiv \frac{v_f t}{D_{f0}} We^{-1/4} \left(\frac{\rho_c}{\rho_f} \right)^{1/2} \left(\frac{\rho_f}{\rho_f - \rho_c} \right)^{1/4} \quad (4)$$

Our results currently indicate that both dimensionless times adequately correlate the data; we now use T^* as the dimensionless time where t is the time after the fuel parcel has entered the water pool. If Taylor instabilities are truly the main mixing mechanism then t^* may be a more general formulation. The fuel-coolant mixture volume for a parcel i is given by

$$V_{m_i} = 3V_{f_i}(T^*)^2 \quad (5)$$

where the fuel volume is given by

$$V_{f_i} = \frac{mf_i}{\rho_f} \quad (6)$$

The volume fractions of fuel and steam in the volume are given by

$$\alpha_{f_i} = V_f/V_m = \frac{1}{3(T^*)^2} \quad (7)$$

and

$$\alpha_{v_o} = \frac{1}{2} - \frac{1}{3(T^*)^2} \quad (8)$$

Because these correlations are based on the FITS experiments performed at one ambient pressure, we must also include a correction term for pressure

$$\alpha_{v_i} = \alpha_{v_o} \left(\frac{P_o}{P_g} \right) \left(\frac{T_{sat}(P_g)}{T_{sat}(P_o)} \right) \quad (9)$$

where P_o and $T_{sat}(P_o)$ are based on the FITS reference pressure. The coolant volume fraction is then

$$\alpha_{c_i} = 1 - \alpha_{f_i} - \alpha_{v_i}$$

Finally, the fuel melt fragment size is taken to be

$$D_{f_i} = D_{f_o_i} \exp(-T^*) \quad (10)$$

where we have assumed a mathematical form similar to that used by Buchanan [14].

Now there are two physical limits to this mixing phenomena that we must consider. As previously mentioned [11], one is due to fluidization of the fuel particles by the steam produced by heat transfer to the coolant liquid (eqn. 2). This limit is a function of the fuel temperature, the water depth, since $H_c \sim \sqrt{t}$, the fuel initial size, D_{f_o} , and the mixing phenomena as empirically given by eqns. 3-10. If we combine these equations and solve for the fuel diameter after mixing as a function of H_c and D_{f_o} , the result is Figure 4. In this figure the fuel diameter after mixing is given for a specific depth, H_c and diameter, D_{f_o} . We also plot the fluidization limit for different fuel temperatures assuming black body radiation.

All the diameters to the left of the fluidization mixing limit for a given fuel temperature can mix without fluidization while those diameters to the right of the limit for a given H_c and D_{f_o} will begin to fluidize. Notice that as H_c increases the minimum diameter for mixing (given by the intersection of the diameter curve and the mixing limit temperature curve) increases significantly.

The other limit is that the fuel-coolant mixture volume will not always continue to grow in size. At some point in time it will reach an upper limit value. To understand why, consider the physical reason for the fuel parcel dispersion. As the fuel breaks apart due to Weber forces the axial pressure gradient across the mixture is imbalanced with the axial pressure gradient within the water pool. This creates a radial pressure gradient causing the fuel droplets to be pushed radially outward by the steam being produced in the mixture. This radial outward growth will continue until the axial pressure drop within and without the mixture is equal. If we equate these axial pressure drops using a homogeneous model we get for fuel parcel i

$$\rho_c g = \left(\frac{\alpha_{f_i}}{1-\alpha_{f_i}} \right)^2 \frac{4C_D G^2}{(\rho_v + \rho_c) D_{f_i}} + \frac{(\rho_v + \rho_c) g}{2} + G^2 \left(\frac{\alpha_{f_i}}{1-\alpha_{f_i}} \right)^2 r_2 \frac{dx}{dz} \quad (11)$$

where

$$G = \frac{(\rho_v + \rho_c)}{2} v_f \quad (12)$$

and $\frac{dx}{dz}$ is the axial quality gradient

$$\frac{dx}{dz} = \frac{6q''_{DROP}}{G D_{f_i} f_g} \quad (13)$$

and r_2 is the acceleration pressure drop parameter

$$r_2 = \left[\frac{4x}{\rho_v} - \frac{4(1-x)}{\rho_c} \right] + \left(\frac{\rho_c}{\rho_v} \right) \left(\frac{0.5}{1-x} \right) \left[\frac{4(1-x)^2}{\rho_c} - \frac{4x^2}{\rho_v} \right] \quad (14)$$

Given a specific fuel-coolant combination, fuel diameter, fall velocity, and temperature and ambient pressure we can solve for the fuel volume fraction, α_{f_i} , when the fuel-coolant mixture stops expanding. The result for the FITS tests is given in Figure 5. Notice that as the velocity increases or the fuel diameter decreases the minimum fuel volume fraction decreases (i.e. maximum mixture volume increases). Both an increase in v_f or a decrease in D_f cause the axial pressure gradient to be larger thereby causing a larger radial expansion; i.e. larger V_m and smaller α_f . This physical limit can also be included in the mixing model.

Mass and Energy Balances

Each fuel parcel can transfer energy with the gases and water as it falls to the water pool base; this may be due to heat transport, chemical reaction, and decay heating. We model each fuel parcel, i , in a lumped parameter fashion

$$m_{f,i} c_f \frac{dT_{f,i}}{dt} = -\dot{Q}_{OUT,i} + \dot{Q}_{IN,i} + \dot{Q}_{DCY,i} \quad (15)$$

where the Lagrangian parcels masses are constant in time. The energy lost by the fuel due to heat transfer, \dot{Q}_{OUT} , is given by

$$\dot{Q}_{TOT,i} = h_{TOT,i} A_{f,i} (T_{f,i} - T_{sat,c}) \quad (16)$$

where the fuel surface area, $A_{f,i}$, is

$$A_{f,i} = \frac{6m_{f,i}}{\rho_f D_{f,i}} \quad (17)$$

and the total heat transfer coefficient, h_{TOT} , is composed of radiative, h_{rad} , convective, h_{film} , and conductive, h_c , parts

$$h_{TOT,i}^{-1} = h_{f,i}^{-1} + (h_{rad,i} + h_{film,i})^{-1} \quad (18)$$

The coefficient of heat transfer in the fuel is given by

$$h_{f,i} = \max \left[\frac{2k_f}{D_{f,i}}, \frac{k_f}{\sqrt{\pi a_f t_i}} \right] \quad (19)$$

where t_i is the time after the fuel parcel has been submerged. The radiative component is given by a standard gray body formulation

$$h_{rad,i} = \frac{F \sigma_r (T_f^4 - T_{sat,c}^4)}{(T_f - T_{sat,c})} \quad (20)$$

where

$$F \equiv \frac{1}{\left(\frac{1-\epsilon_c}{\epsilon_c} \right) + 1 + \frac{A_{c,i}(1-\epsilon_f)}{A_{f,i}\epsilon_f}} \quad (21)$$

For heat transfer through the film, we assume conduction dominates the process

$$h_{film,i} = \frac{k_v}{\delta_i} \quad (22)$$

where

$$\delta_i = \max \left[\frac{\alpha_{v,i} v_{mix} D_{f,i}}{\pi D_{f,i}^3}, \delta_{0,i} \right] \quad (23)$$

$$\delta_{0,i} = 2 \left[\frac{k_v \mu_v D_{f,i} (T_f - T_{sat,c})}{\rho_v (\rho_c - \rho_v) g l_{f,g}} \right]^{1/4} \quad (24)$$

Now the energy gained by chemical reactions, $\dot{Q}_{IN,i}$, would be present if the fuel is partially metallic and steam oxidizes it producing ZrO_2 , Cr_2O_3 or Fe_2O_3 . We have modelled this quite simply by

$$\dot{Q}_{IN,i} = \dot{m}_H'' A_{f,i} X_{f,m} i_{reac} \quad (25)$$

where $A_{f,i}$ has been previously defined, $X_{f,m}$ is the fraction of metal, and i_{reac} is the heat of reaction per kg of hydrogen produced for one of the three oxides mentioned above. Now the mass flux of hydrogen, \dot{m}_H'' , is equal to the molar flux, \dot{N}'' , times the molecular weight where

$$\frac{d(N/A)}{dt} = \frac{D_o \Delta P}{R_o T_v} \quad (26)$$

where we have modelled the mass transfer coefficient D_o , by

$$D_o = \frac{2D_H}{z_i} \quad (27)$$

This model for hydrogen production is based on the observation [15] that the majority of hydrogen produced occurs while the fuel is molten. Finally, $\dot{Q}_{DCY,i}$ is the decay heat energy in the fuel, given by correlations.

The fuel parcels release their energy to the water pool as they fall through it. The water pool mass balance is then

$$\frac{dm_c}{dt} = -\dot{m}_v \quad (28)$$

where

$$\dot{m}_v = \frac{\dot{Q}_{OUT} - \dot{Q}_c}{i_{f,g} + c_c (T_{sat,c} - T_c)}$$

and \dot{Q}_{OUT} and \dot{Q}_c are the summation of the heat transfer rates from all submerged fuel parcels; i.e. $\dot{Q}_{OUT} = \sum_i \dot{Q}_{OUT,i}$ and $\dot{Q}_c = \sum_i \dot{Q}_{c,i}$ for

$$\dot{Q}_{c,i} = h_{c,i} A_{c,i} (T_{sat,c} - T_c) \quad (29)$$

where

$$h_{c,i} = \frac{k_c}{\sqrt{\pi a_c t_i}} \quad (30)$$

$$A_{c,i} = \frac{6(\alpha_{st,i} + \alpha_{f,i}) v_{mix}}{(D_{f,i} + 2\delta)} \quad (31)$$

The water coolant energy balance is

$$\frac{dU_c}{dt} = -\dot{m}_v c_c (T_c - T_{ref}) + \dot{Q}_c \quad (32)$$

where U_c is total coolant internal energy and the coolant temperature is found by an equation of state

$$T_c = f(U_c, m_c) \quad (33)$$

The steam and hydrogen produced by the fuel-coolant mixing flow into the gas atmosphere adding to its mass and energy,

$$\frac{dm_g}{dt} = \dot{m}_v + \dot{m}_H - \dot{m}_{gOUT} \quad (34)$$

$$\begin{aligned} \frac{dU_g}{dt} = & \dot{m}_v (i_{fg} + (T_{satc} - T_{ref})) \\ & + \dot{m}_H C_{pH} (T_f - T_{ref}) - \dot{m}_{gOUT} i_g \end{aligned} \quad (35)$$

where we back calculate for T_g

$$T_g = f(U_g, m_g) \quad (36)$$

and recalculate the new properties for the gas; mixture specific heat, mixture gas constant, pressure and water coolant saturation temperature

$$P_g = m_g R T_g / V_g \quad (37)$$

$$T_{satc} = T_{sat}(P_g) \quad (38)$$

The volume of the gas atmosphere is determined by the initial geometry and updated by the momentum equation if the water pool is displaced, or if some of the gas flows out of the volume, \dot{m}_{OUT} .

The fuel parcel which eventually falls to the coolant pool is either accumulated in a debris bed or molten pool. If the fuel parcel temperature is above its melting point it is added to the molten pool; if not it is added to the debris bed.

Momentum Balance

As steam and hydrogen are generated and flow into the gas atmosphere during fuel discharge into the water pool, the pressure will rise. This rise in pressure will cause a pressure imbalance with volumes connected to this 'cavity', and gas or liquid flow would be induced. This is especially important to consider when modelling ex-vessel phenomena. There are two possible configurations in this cavity (Figure 6). The first is that the water pool depth does not cover the flow path exit, 'tunnel', to an adjoining volume. In this case one would expect primarily a gas flow out of the cavity region. For this case we have modelled the flow rate out of the cavity by a simple incompressible flow Bernoulli equation

$$\dot{m}_{gOUT} = A_{OUT} \left(\frac{2 \rho_g (P_g - P_\infty)}{K_g} \right)^{1/2} \quad (39)$$

where K_g is the flow loss coefficient and A_{OUT} is the flow area. If the water pool covers the exit tunnel then one would expect a different behavior. The gas pressure would probably push out some fraction of the water pool first as a coherent slug of material. At this time we are developing a simple expansion model for this situation.

Numerical Solution

The balance equations and constitutive relations just discussed are written in conservative difference form and integrated numerically using, currently, a simple Euler integration technique. This method of solution requires very small time-steps (1 msec for heat transfer calculations), but has the great advantage of being quite transparent for future modifications of heat transfer models and mixing correlations. In future versions of the computer model more sophisticated numerical techniques will be used. We also have incorporated into the computer model mass and energy conservation-check calculations to verify that at each time step the total mass and energy of each component is conserved. This then reduces our concerns to the rate of mass and energy partitioning rather than their overall conservation in our calculations.

Model Sample Calculations

A sample calculation was performed using this transient model. We chose the Sandia FITS-1G experiment [13] as our test problem; it involved a simulant fuel mass poured (iron-alumina, 20.4 kg) into nearly saturated water (44.4 kg @ 367K, $T_{sat} = 368.5$ K). This experiment is a good first test problem because the geometry is relatively simple (square plexiglas water chamber, 0.46 m square and 0.21 m water depth) and an energetic fuel-coolant interaction (steam explosion) did not occur; rather the fuel poured into the water pool, mixed with the water, fell to the chamber base, and quenched. Because an energetic fuel-coolant interaction was purposely avoided in this experiment the fuel mass entered the water pool at a relatively high velocity (8 m/s) and as a long thin stringy mass (L/D=15). We modelled the entering fuel mass as consisting of a number of Lagrangian fuel parcels (12) with a diameter of 0.08 m and a total length of 1.05 m. The initial fuel temperature was approximately 2700 K, and the fuel was assumed to be a homogeneous mixture of molten iron and alumina. Because the water mass was small and the depth quite shallow fuel-coolant mixing occurred in about 0.2 sec. After this time the fuel settled on the chamber base and slowly quenched.

For our sample calculation, the calculated fuel temperature decreases slightly during its fall through the water pool. This result is reasonable if one compares the energy loss rate from the fuel (dominated by radiation) to the energy gained by the exothermic oxidation of iron. One finds that the fuel temperature should decrease, but only slightly compared to its initial temperature. Our model for fuel mixing and breakup indicates that the fuel breakup from 0.08 m to 0.015 m during its fall through the water pool. This result is consistent with the post-test examination of the fuel debris where fragments of this final size range were measured.

Some of the results of the calculation are presented in Figures 7 and 8; gas pressure and water level as a function of time, and the amount of steam and hydrogen generated. Notice that the pressure and water level rise monotonically as the fuel pours into the water pool and mixes with it. After all the fuel has settled on the interaction chamber base the water swell height decreases, as does the pressure slightly. The change in the slope of the pressure history after the fuel has settled on the chamber base is physical, because the water level has decreased slightly; what is not physical is that the pressure remains constant at this point. In the current model we have neglected energy transfer from the accumulated molten fuel pool and the overlying water on the chamber base. Actually the pressure rise rate would change, because of the change in the heat transfer area, but would not remain constant.

Figure 8 indicates that the amount of steam produced during the fuel fall through the water pool is much larger than the hydrogen mass generated. In fact, for this specific case the hydrogen produced corresponds to much less than one percent of the metallic fuel mass reacted. The reason for this is that the calculated vapor film thickness around the fuel droplets is rather large (1-10 mm) and therefore, the rate of diffusion of steam through the hydrogen to the fuel surface is small (remember the diffusion rate is inversely proportional to the film thickness). Now this calculated thickness may be an overestimate of the correct film thickness, because we have assumed in the model that all of the steam remaining in the fuel-coolant mixture as the fuel falls through the water pool surrounds the fuel droplets. This simplification can be relaxed and we could consider only a laminar flowing film layer; however, because the amount of hydrogen produced during this time so small it is our belief this is not warranted at this time.

Current Conclusions

A dynamic model for fuel-coolant interactions is being developed to describe the transient process when fuel mixes with water in a process when fuel mixes with water in a pouring mode of contact. The model currently can calculate the rate of steam and hydrogen generation as the fuel mixes with water. The computer model is based on a lumped parameter control volume modelling approach which utilizes explicit numerical solution techniques and successfully conserves mass and energy at every time step. It currently uses empirical correlations to model the fuel-coolant mixing behavior.

Sample calculations of the FITS-1G test at Sandia indicate that in the absence of an explosion very small amounts of hydrogen are generated (less than a few percent of metallic fuel reacted). The model is now being developed to consider fuel-coolant interactions after mixing has occurred. It can be used to model ex-vessel cavity phenomena that occur during fuel discharge into the reactor cavity and related steam spike phenomena and provide initial conditions for possible molten core-concrete interactions.

Nomenclature

| | |
|-------------------|---|
| a | - thermal diffusivity |
| A | - area |
| c | - specific heat |
| C _D | - drag coefficient for sphere (~ 1) |
| D _H | - diffusion coefficient between H ₂ and H ₂ O |
| D | - diameter |
| E | - mixing energy |
| F ^m | - view factor for radiative energy transfer |
| g | - gravitational acceleration |
| h | - heat transfer coefficient |
| H _C | - depth of the water pool |
| i | - enthalpy |
| i _f | - latent heat of vaporization |
| k _g | - thermal conductivity |
| m | - mass |
| N | - number of moles |
| ΔP | - steam partial pressure difference between the ambient and at the fuel surface |
| P | - pressure |
| P _{amb} | - ambient pressure |
| q ₁ | - heat flux |
| q _{DROP} | - $F_G (T_F^4 - T_{sat}^4) + h_V (T_F - T_{sat})$ |
| R _o | - universal gas constant |
| T | - temperature |
| T _V | - $(T_{sat} + T_F)/2$ |
| u | - internal energy |
| v | - velocity |
| V | - volume |
| x | - mass fraction |
| α | - void fraction |
| δ | - vapor film thickness |
| ϵ | - emissivity |
| ρ | - density |
| σ | - Stephan Boltzman constant |

Subscripts

| | |
|----------------|-----------------|
| b | - breakup |
| c | - coolant |
| d | - displaced |
| FR | - fuel fragment |
| f | - fuel |
| g | - gas |
| H ₂ | - hydrogen |
| o | - initial |
| M | - mixture |
| MIN | - minimum |
| v | - coolant vapor |
| sat | - saturated |

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Figure 1

CONCEPTUAL PICTURE OF FUEL-COOLANT MIXING

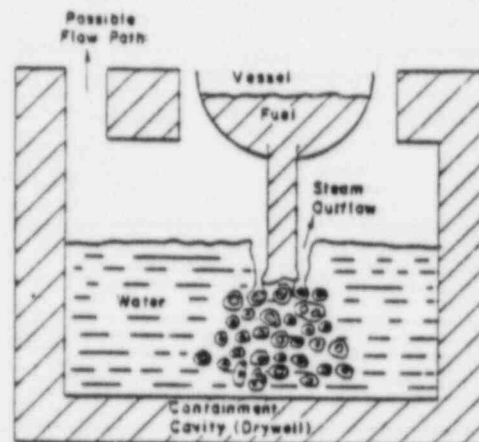


Figure 2

COMPUTER MODEL OF FUEL-COOLANT MIXING

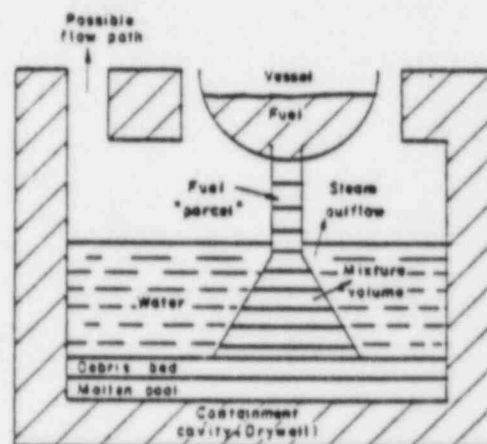


Figure 3 - The Dimensionless Mixture Volume as a function of a Derived Dimensionless Time (t^*)

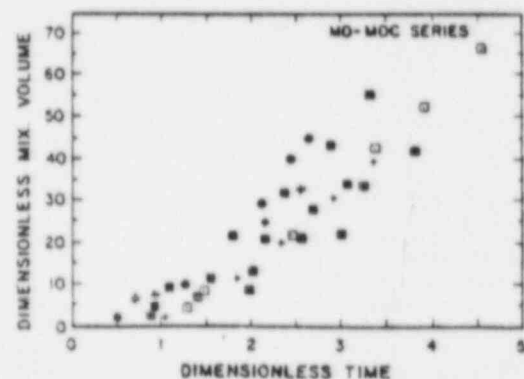


Figure 4 - Fuel-Coolant Mixing and the Fluidization Limit as a Function of the Coolant Depth and Fuel Diameter

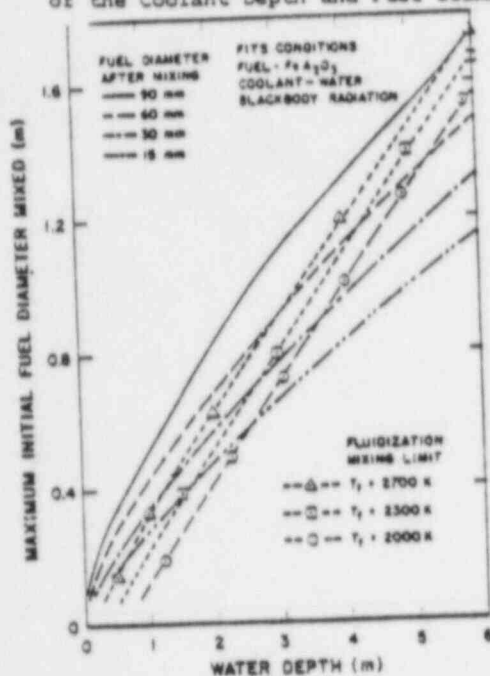


Figure 6 - Conceptual Picture of Fuel-Coolant Expansion Dynamics in the Reactor Cavity

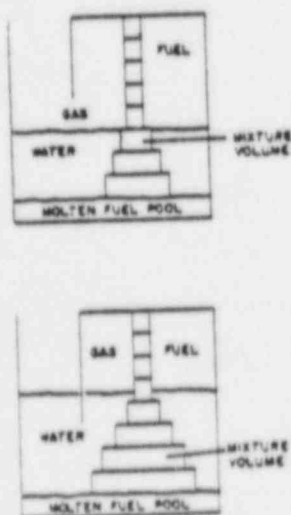


Figure 5 - The Minimum Fuel Volume Fraction as a function of the Fuel Velocity and the Diameter

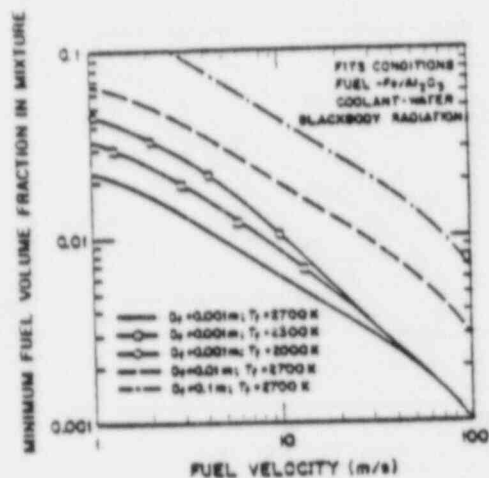


Figure 7 - FITS-1G Gas Chamber Pressure and Water Mixture Level as a Function of Time

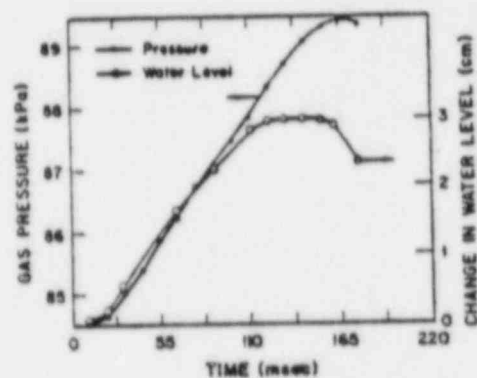


Figure 8 - Gas Mass as a function of Time for FITS-1G

