TID--26993

THERMAL-HYDRAULIC TRANSIENTS WITH COOLANT AND CORE
MATERIALS IN LMFBR SAFETY EVALUATIONS

Quarterly Progress Report

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September 1, 1975 - November 30, 1975

Prepared for the U. S. Nuclear Regulatory Commission under contract
no. AT(49-24)-0181.

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HIGHLIGHTS FOR SEPT.-NOV. 1975

Task I - Thermal-Hydraulics of LOFA Initiating Phase

A stable solution for the early, two-dimensional, boiling (voiding) regime was obtained. This solution has all the expected qualitative features, including flow diversion (of the liquid) around the two-phase zone, pressure build-up and boiling zone growth in all directions (with a bias in the downstream direction).

Experimental data relevant to clad relocation dynamics were obtained for conditions exceeding the flooding threshold. The main difficulty in performing such experiments originates with small melting non-uniformities of the metallic film. This behavior provides for the gradual removal of small film segments and, hence, prevents the formation of a reasonable size molten layer required for the hydrodynamic measurements and observations. Further, it can be responsible for localized material build-up and thus possibly atypical flow regime transitions.

Efforts to incorporate the quantitative aspects of the previously presented clad relocation flow regime maps in the SAS calculation were initiated, and preliminary results were obtained, in cooperation with REG, for CRBRP loss-of-flow analysis.

Task II - Recriticality Consideration

A major effort was expended in reviewing and assessing the Board and Hall calculations for energetic fuel coolant interactions. As an outgrowth of this study an experimental program was defined, and presently being negotiated, for a closer examination of the basic mechanism invoked by Board and Hall for fragmentation.

Task III - General Consulting

A substantial effort was expended in reviewing ANL/RAS 75-29 and Appendix F to the CRBRP PSAR in detail. Participated in the REG effort for formulation of the Q-1's.

TASK I - THERMAL-HYDRAULICS OF LOFA INITIATING PHASE

I.1 Voiding Dynamics

Work with the first version of the 2D Boiling Model (2DBM-1) progressed to the attainment of a stable, well behaved solution. The early, two-dimensional boiling regime was seen to evolve along the expected, qualitatively, direction. In these initial cases a cosine power distribution, both in the axial and radial, direction, was utilized for the purpose of initiating boiling in a small central region of the subassembly.

Since both the source term, and the auxiliary conditions exhibit cylindrical symmetry the differential field equations were specialized in the r-Z geometry. By means of a volume averaging operation the multiconnected subassembly field was transformed into an equivalent continuum. The two-phase zone is treated according to a homogeneous-equilibrium approximation. This would appear sufficient for the early stages of the boiling process. Vapor slip will be introduced in a future version.

The solution for the pressure and velocity fields is presented in two-space dimensions for two time instances in Figures 1-4.* The local liquid flow diversion, and the pressure buildup around the boiling, two-phase zone may be easily seen. Further, the resulting reduction in inlet flow and growth of the boiling zone are also clearly discernible. The challenge in these computations is due to the presence of subcooled and boiling fields coupled with a free boundary.

Certain programming improvements are being planned for improving computational time. A finite element formulation has been also completed and programming is underway for examining the feasibility of an algorithm resulting to drastic cuts in computational effort. The currently employed finite-difference scheme is adequate for studying the fundamental characteristics of two-dimensional boiling and hence assess basic similarities (differences) between various size bundles. For system-oriented computations, however, a more efficient computation (with less storage requirements) would be necessary and for this reason the finite-element studies have been initiated.

*The Figures may be found at the end of the report.

The next major goal in the development of the two-dimensional boiling model is to incorporate (couple) a fuel pin model and thus affect the correct distribution Q for arbitrary space-time power density distributions. A novel finite-element thermo-elastic pin formulation, including temperature dependent properties, has been developed and programmed. Certain case runs showed excellent agreement with exact solutions and trivial computational effort. More details on these studies will be reported in the next quarterly.

The experimental work in the areas of two-dimensional boiling (non-metallic fluids) and chugging phenomena (liquid metals) is in the preparatory stage. Details of those preparations will be provided in the next quarterly.

I.2 Cladding Motion

It has been previously determined[1,2] that the initial clad relocation, following melting, will be, for CRBRP LOFA conditions, in the upward direction. Radial melting incoherencies, due to initial temperature profile, would reduce but not completely negate this upward motion. For typical conditions this velocity has been estimated at a few feet per second.

These conclusions were based upon: (a) experimental determination and correlation of the flooding inception with metallic and non-metallic films, and experimental conditions including various degrees of radial incoherency (bypass) [3], and (b) a calculation using an annular flow regime hypothesis. This hypothesis was conjectured from our experimental observations indicating that maximum film instability, accompanied by large waves and hence potential for bridging the flow passages, occurred around the point of incipient flooding. For conditions clearly exceeding flooding, wave formation was minimal and this behavior was further augmented by film thinning (depletion) due to upward relocation.

Direct experimental verification of these results however, was hampered by difficulties in producing "sizable" molten films for conditions exceeding the flooding limit. Due to melting non-uniformities small patches of liquid film first appeared, and were rapidly transported away prior to merging into a uniform "macroscopic" film. Our efforts were therefore directed, during this quarter, at improving our melting technique.

Considerable effort was expended with various direct electrical heating options with negative results. We have finally concluded this search with a radiation heating method. A bank of infrared lamps, 2 kw power each, was placed immediately behind the test section (similar to that utilized previously [3]). The test section surface upon which the liquid film is to be formed, was machined down to 0.025". This method provides an essentially uniform (instantaneous) film and allows for good control of the temperature profile, downstream of the test section, which is useful for observing the phenomenology of freezing and plugging and its interaction with the flooding and relocation process. This experiment is now at the production stage, with a large number of runs already completed for the old test section. Synchronized motion pictures, pressure drop and gas flow measurement have been obtained and are presently under analysis and evaluation. Another major improvement in these experiments is also due to the achievement of essentially constant pressure drop across the test section (i.e. ΔP remains constant as the metal film is melting and set in motion). For the condition expected the major portion of the film was transported downstream and froze quickly as it entered the cold zone of the test section.

Due to this upper plug the gas flow rate was drastically reduced and in many cases the remaining molten clad drained and froze in the test section inlet cold zone. At the completion of each run the test section was carefully disassembled and the solidified metal pattern was reconstructed (on a sheet of paper). The photos shown in Figures 5 and 6 are representative examples of this type of, so to speak, post-mortem analysis. Additional details of those experiments will be provided in the next quarterly. Future experiments are planned, with new test section geometries, in order to gain insight to additional aspects of the clad relocation problem.

For the purpose of accident analyses all that is needed is the rate at which cladding is removed from the core region. The SAS calculation utilizes CLAZAS which in addition to neglecting radial incoherency effects has certain modeling peculiarities that lead into excessive clad relocation velocities and large power transients. A simple model, instead, taking into account incoherency effects may be formulated in such a manner as to

provide a more reasonable upper bound cladding relocation rate than that given by CLAZAS. The initial velocity corresponding to initial melt profile and available pressure drop may be located (point A) on the flow regime map corresponding to initial void fraction $\alpha = 0.76$, Fig.7. Now as the cladding is relocated several things happen at the same time: (a) the void fraction in initially molten region increases due to cladding depletion: the effect is to slightly increase the clad velocity (portion of the increase due to increased gas velocity is compensated by change in the friction factor with void fraction), (b) additional cladding will melt (in the downward direction primarily) thus increasing the value of $\tilde{L}$: the effect will be to move the point A in the upward direction, (c) additional cladding will melt in the radial direction, thus increasing the value of $\tilde{A}_w$: the effect being to move the point A to the right, and (d) some freezing and plugging will occur at the end of the active core region: the effect being to decrease somewhat, the sodium vapor streaming and thus diminish the effectively available pressure gradient for clad levitation. In general, therefore, the point A will write a trajectory in the $\tilde{L}_w - \tilde{A}_w$ diagram. This trajectory, being in general to the top-right direction will determine roughly the relocation-rate history. The trend will be towards decreasing velocities. The net upward relocation process will cease when the contour corresponding to a value of $j_g^* = 1$ (for the particular pressure gradient condition) is reached. A period of chaotic two-phase fluidization process will then commence. However, due to the limited amount of molten cladding available and the nature of the two-phase flow pattern net draining is not likely to commence until a value of $j_g^* = 0.5$ is reached.

It is expected that the overall calculation would not be sensitive to the details of the trajectory of point A discussed above. A straight-line approximation may be constructed from a determination of axial and radial melting rates in the neighborhood of point A. Having established this trajectory the calculation within the SAS framework is readily done. As SAS calculates melting of the axial clad segments, the $\tilde{L}_w = \tilde{L}_w(t)$ is established and through the trajectory previously discussed velocities can be assigned to each one, appropriately. Further sensitivity studies and certain extreme conditions can readily be accomplished by affecting

the necessary changes on the initial position of A and its subsequent trajectory. This scheme is now being implemented in cooperation with REG for the CRBRP application.

I.3 Freezing and Plugging

It has been recently argued [4] that if cladding were to relocate in the upward direction the potential for freezing and plugging in the blanket region (of the CRBRP) would be significantly less than that found in the inconel reflector region of the FFTF reactor and the R-4 and R-5 TREAT "simulations"[5]. In the latter case the great potential for plugging manifested itself by the rapid formation of a thin upper steel plug and subsequent draining (following sodium vapor flow cutoff) of the remaining clad and plugging of the lower end of the core. In fact, a major fraction of the clad appears to have drained prior to fuel melting [6]. The difference in behavior of the CRBR blanket was argued on the basis of the poor conductivity of the blanket fuel in comparison to that of the inconel material. Indeed, although the heat capacity per unit volume is similar for all three materials, fuel, inconel (reflector), and 316 type stainless steel (cladding), the thermal conductivity of the former is by a factor roughly of 10 smaller than that of the latter two. In the following simple analysis we will show that even such a great difference in thermal conductivity cannot introduce a reduction greater than 50% in plugging potential.

We define a measure of the plugging potential by the constant factor, R, appearing in the well known expression for the rate of solid layer buildup:

$$\frac{ds(t)}{dt} = \lambda \sqrt{\alpha_s} t^{-1/2} \equiv R/\sqrt{t} \quad (1)$$

Where $s(t)$ is the solidified layer in time t , α_s is the thermal diffusivity of the solidifying material and λ is given by:

$$\lambda \exp\{\lambda^2\} \left\{ \frac{k_s \sqrt{\alpha_b}}{k_b \sqrt{\alpha_s}} + \operatorname{erf} \lambda \right\} = \frac{\hat{C}_s \Delta T}{L \sqrt{\pi}} \equiv f \quad (2)$$

Here, k_s , α_s , and $\hat{C}_s$ are thermal conductivity, thermal diffusivity and heat capacity (per unit mass) of the solidifying material, k_b and α_b are the corresponding properties of the cold material serving as a "base" for solidification and L is the latent heat of fusion. ΔT is the total available temperature driving force for solidification.

For conditions of interest $\Delta T \sim 800^{\circ}\text{C}$ (somewhere, in fact, between 600°C and 900°C), $L = 66 \text{ cal/g}$, and $\hat{C}_p = 0.18 \text{ cal/g}^{\circ}\text{C}$. This produces a value of $f = 1.23$. For steel solidifying on steel (or inconel), the first term in the brackets of Eq.(2) is unity and we must solve

$$\lambda \exp \{\lambda^2\} [1 + \operatorname{erf} \lambda] = 1.23 \quad (3)$$

A value of 0.56 is obtained for λ . Now, for steel solidifying on fuel, we have:

$$\frac{k_s \sqrt{\alpha_F}}{k_F \sqrt{\alpha_s}} \approx \frac{k_s}{k_F} \approx 4$$

The equation for λ , therefore, becomes:

$$\lambda \exp \{\lambda^2\} [4 + \operatorname{erf} \lambda] = 1.23$$

from which we obtain $\lambda = 0.27$.

It can be easily seen, therefore, that more than one-order-of-magnitude reduction in thermal conductivity of the base material, yields only a 50% reduction in the growth constant λ . This implies that solidification proceeds at one-half the rate in the second case. It should also be pointed out that the actual available ΔT will be greater in the second case since due to the low thermal conductivity the fuel will tend to heat up at a slower rate than the inconel in the time period between transient initiation and clad melting. This expected bias in ΔT will tend to further reduce the difference in the growth rate constants of the two cases.

To further clarify the sensitivity (or insensitivity) of the freezing rate upon the thermal conductivity of the materials involved, assuming equal heat capacities per unit volume as is the case for fuel and steel, we have constructed Figure 8. The value of λ (growth constant) is shown as a function of the ratio of the thermal conductivities, for the typical value of $f = 1.23$. It is seen that in going from a ratio of one (steel solidifying on steel) to a value of zero (steel solidifying on a material with extremely, "infinite," high thermal conductivity) the growth constant

increases only by 44%. In going in the opposite direction, say a value of 16 (steel solidifying on fuel) yield a reduction in the growth constant only by 53%.

To better understand the physical origin of the non-linearity for high values of k_s/k_F (Fig. 8) consider the following:

We postulate that the heat transfer in the poor thermal conductivity material controls the solidification rate. That is, for liquid steel at its melting temperature, T_m , both the liquid steel and the solidified steel layer, at any time, would remain at T_m . For initial fuel temperature T_o , all the temperature gradient would be "contained" within the fuel region. For transient conduction in this region, we find the total heat absorbed in the fuel up to time T as:

$$q_{TOT} = 2k_F \frac{(T_m - T_o)}{\sqrt{\pi\alpha_F}} \sqrt{T}$$

The total steel solidified in time T is:

$$X = 2\lambda\sqrt{\alpha_S T}$$

Equating the amount of latent heat associated with this steel to that absorbed by the fuel, we have after some simplifications:

$$\lambda \sqrt{\frac{k_s}{k_F}} = \frac{(T_m - T_o)\hat{C}}{L\sqrt{\pi}} \equiv f = 1.23$$

For every ratio of thermal conductivities a value of λ can thus be found. This relation is shown by the broken line of Figure 8. It is seen that as the ratio k_s/k_F increases the two approaches tend to agree indicating that the heat conduction within the fuel is truly controlling the process. It is seen that such control is essentially complete by the time the conductivities differ by one order of magnitude. Further the sharp non-linearity of the k_s/k_F vs λ curve is explained with this very simple model. Finally when $k_s/k_F \gg 1$, by combining the above equations we find that the thermal conductivity of the steel does not, as it should, enter the rate of solidification expression:

$$X = 2\lambda\sqrt{\alpha_s T} = 2\sqrt{k_F} \frac{(T_m - T_o)\hat{C}}{L\sqrt{\pi}} \sqrt{\frac{T}{\rho\hat{C}}} = 2 \frac{(T_m - T_o)\hat{C}}{L\sqrt{\pi}} \sqrt{\alpha_F T} = 2f\sqrt{\alpha_F T}$$

Experimental studies on freezing and plugging processes, in the apparatus described earlier [1], are continuing. Certain modifications for improved operational convenience were indicated by the earlier experimentation and have been in progress. The immediate effort is directed at the problem of solidification with wall ablation. More precise and complete profiles of ablated material distribution of the type reported earlier [1], will be obtained for the purpose of guiding mathematical model development. These results will be reported in the next quarterly.

TASK II - RECRITICALITY CONSIDERATIONS

II.1 Boiling Pool Dynamics

The test section for the experiments specified previously, is under construction. Associated instrumentation and electronics are on order. Initial experimentation is expected to commence by the end of the next quarter.

A substantial parallel effort was devoted in examining the feasibility and potential advantages of utilizing microwave heating for our studies. The results were positive and a research proposal has been submitted and is currently being evaluated by NRC.

An effort in developing a simple pool disassembly calculational tool has been initiated.

II.2 Thermal Interactions at Pool Boundaries

Our primary interest here is from the point of view of potential dynamic phenomena. It has been planned to first review the ANL "upper plenum" and "dissipation" experiments. Since appropriate documentation is not yet available these efforts remained dormant. Experimental plans, also specified, must await the apparatus constructed under II.1. Our primary effort has been directed, therefore, on the related area of fuel-coolant interactions. The Board-Hall hypothesis was reviewed in detail. It was concluded that uncertainties in the calculations of the characteristics time for fragmentation, due to the large extrapolations needed for liquid/liquid system calculations, and its closeness to the time needed for acceleration, raise serious question on the viability of the fundamental mechanism invoked by Board and Hall. An experiment was designed and an experimental program was specified for an examination of these quations. A research proposal was prepared and it it now being evaluated by the NRC.

TASK III - GENERAL CONSULTING

The principal investigator has been in close contact with the REG staff for consultation and carrying out certain cooperative efforts.

The primary effort in this area has been devoted in detailed review of the CRBRP PSAR App. F and ANL/RAS 75-29. The principal investigator contributed in the formulation of the first round questions sent out in Dec. 1975.

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6. M. Ishii et al, "One-Dimensional Clad Relocation Model for Fast Reactor Loss-of-Flow Accidents," ANL/RAS 75-22, Aug. 1975.

VELOCITY CHANGE AT TIME STEP = 1099
(1.099×10^{-3} SECONDS)

Figure 1. Velocity field as determined by 2DBM-1 at ~ 1 msec.

VELOCITY CHANGE AT TIME STEP = 2099
 $(2.099 \times 10^{-3} \text{ SECONDS})$

Figure 2. Velocity field as determined by 2DBM-1 at ~ 2 msec.

PRESSURE FIELD CHANGE AT TIME STEP = 1099 (1.099×10^{-3} SECONDS)

Figure 3. Pressure field as determined by 2DBM-1 at ~ 1 msec.

PRESSURE FIELD CHANGE AT TIME STEP = 2099 (2.099×10^{-3} SECONDS)

Figure 4. Pressure field as determined by 2DBM-1 at ~ 2 msec.

Figure 5. Typical solidified metal pattern, indicating top plug, for gas velocity exceeding flooding limit.

Figure 6. Typical solidified metal pattern, indicating top plug, for gas velocity exceeding flooding limit.

Figure 7. Graphical solution for j_g^* in terms of $\tilde{L}_w$, $\tilde{A}_w$ and m assuming annular flow and $\alpha = 0.76$, and trajectory indicating possible time evolution of flow patterns for CRBRP clad relocation.