THERMOHYDRAULIC LMFBR SAFETY EXPERIMENTS

**QUARTERLY REPORT
APRIL - JUNE 1976**

M.S. KAZIMI, Principal Investigator

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**FAST REACTOR SAFETY DIVISION
DEPARTMENT OF APPLIED SCIENCE
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UPTON, NEW YORK 11973**

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J.C. CHEN, M.H. CHUN, AND W.R. GUSTAVSON

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I. INTRODUCTION

I.A Scope of Work

Analysis of the behavior of the liquid metal fast breeder reactor (LMFBR) following a hypothetical accident requires description of several thermohydraulic phenomena. Many such phenomena have not been adequately, if at all, investigated in the past. In the present program at BNL, experimental and analytical efforts will be undertaken to improve the understanding of relevant thermohydraulic phenomena, primarily in the areas of post-accident heat removal (PAHR) and transition phase (TP) of a hypothetical core disruptive accident.

In evaluation of the potential for cooling the core materials following a core-disruptive accident, it is important to know the heat loads that will be imposed by the accumulated melt on the surrounding structure. If the heat generation exceeds heat removal, the core debris is likely to evolve into a boiling pool. The occurrence of boiling in the pool of core materials signifies a more serious condition with regard to melting attack on the containment boundary walls. The distribution and magnitude of the heat fluxes from a boiling pool are, therefore, of interest in both in-vessel and ex-vessel PAHR evaluations. In particular, it is important to identify the hot spots, that are the location of highest fluxes, at the container of boiling core materials.

The potential for safe containment of the core materials of a LMFBR following a hypothetical accident depends to a great extent on the post-accident distribution of fuel and other core materials. Upward fuel relocation is likely to be driven by sodium vapor pressure in a transient

overpower accident (TOP), and by fuel or steel vapor pressure in a loss-of-flow (LOF) accident. Molten fuel relocation in the downward direction would be driven by static head pressure in addition to vapor pressure. In either case, if coolant channels are not plugged, ejection of the molten core debris can occur within a few seconds. However, deposition of the molten debris by refreezing on cold structures leads to plugs and the formation of a "bottled" core region. In such a case, fuel dispersal would require melt-out of the plugs or the lower assembly structure, a much slower process. Thus, the phenomena of streaming, i.e. the flow of an initially molten material through channels with cold walls, and the associated transient freezing process is of great importance. Specific interest lies in determining the possibility for either the formation of frozen plugs or, alternately, streaming without plugging under LMFBR conditions.

The post-accident distribution of core materials is to a great extent dependent on the core behavior between initial cladding and fuel melting and the time when sufficient fuel dispersal occurs to render the core subcritical. In a transient overpower accident, subcriticality may occur with relatively small fraction of the core molten. In under-cooling accidents, gross core meltdown is more likely. For the loss-of-flow accident, the development of a high temperature two-phase fuel-steel fluid in the core may be expected. The characteristics of such a two-phase media, with internal heat generation, is of significant influence on the consequences of the accident. For example, if the internal vapor generation rate is sufficiently high, the molten material may be atomized and fluidized. This may lead to rapid

dispersion of the fuel from the core. However, significant uncertainties in the conditions for dispersal and the degree of dispersion exist.

The work plan of this program covers small scale experiments in three areas:

1. Boiling Pool with Internal Heat Generation
2. Streaming Experiments
3. Transition Phase Phenomena

Additionally, an ongoing effort will be directed at delineation of the phenomena of importance to both post accident heat removal and transition phase analyses.

I.B. Summary of Progress

1. The void fraction measurements in internally heated boiling pools of $\text{ZnSO}_4\text{-H}_2\text{O}$ solution have been made for specific internal power in the pool up to 2 cal/sec cm^3 of liquid volume. The average void fractions obtained indicate that very high (> 0.7) void fractions in the pool may occur, depending on the flow regime. However, the trend of minimum void fractions in the pool seem to follow the predicted behavior if the pool is assumed to be in the churn-turbulent flow regime. The current measurements indicate that if the boiling heat rate in a molten fuel pool is $\sim 1\%$ of nominal operating specific power, the average void fraction in the pool is expected to be at least 40%.

2. All the data obtained in the streaming/freezing experiments using paraffin wax have been analyzed. It is concluded that the streaming rate is highly dependent on the initial fluid temperature, driving pressure and channel diameter.

The tests using Wood's metal have begun.

3. Scoping analyses have been performed to assess the effect of mass addition at the boundaries of a heat-generating liquid pool. The results indicate that the downward heat transfer rate could be substantially higher than what may be estimated from the correlations developed for heat generating pools in rigid boundaries.

II. Heat-Generating Boiling Pool Phenomena

The objective of this study is to characterize the heat transfer and fluid dynamics modes in a boiling pool with internal heat generation. Emphasis is placed on measurement of the local variation of the heat transfer rate to the surrounding walls. The heat transfer and fluid dynamics characteristics are studied under various volumetric heating conditions in the pool, cooling rates of the surrounding wall and boiling pool heights.

II.A. Void-Distribution In Volume-Heated Pools

In previous reports¹⁻³, attention has been focused on the heat-transfer characteristics of a boiling volume-heated pool. In the present report the attention will be shifted to fluid-dynamics of such boiling pools.

Characteristics of the flow regimes of internally heated boiling pools have become a subject of interest in analysis of the transition phase of hypothetical loss-of-flow accidents in the LMFBR. Previous investigators⁴⁻⁶ have addressed such characteristics using information generated mainly from experiments involving surface injection of a light fluid into a heavier fluid. In the present study, several tests have been performed to obtain experimental results on the void distribution that may develop in internally heated boiling pools.

The experiments involved electrical heating of a $\text{ZnSO}_4\text{-H}_2\text{O}$ solution in a 7" x 9" x 12" pyrex jar. The power was applied through two parallel copper electrodes which can be cooled as required to prevent preferential nucleation at the electrode surfaces. A pressure probe was used to measure the pressure profile in the pool. The total static head in the pool for each test was kept constant by delivering make-up water through a constant-level weir. The information thus obtained was used to generate a vertical profile of the void fraction

as well as the average void fraction in the pool for several power levels in the pool, up to about 2.0 cal/sec-cm³ of liquid volume.

The data collected from several tests are shown in Figure 1 in terms of the non-dimensional heights h and h_0 defined as:

$$h = \frac{QH}{L\rho_v V_\infty} \quad \text{and} \quad h_0 = \frac{QH_0}{L\rho_v V_\infty} \quad (1)$$

where Q is the boiling heat rate per unit liquid volume, H is the total height of the boiling pool, H_0 is the effective liquid height in the pool, L is the latent heat of vaporization, V_∞ is the terminal rise velocity of a single bubble in the liquid and ρ_v is the vapor density at ambient pressure. Also shown in Figure 1 are the data of Reference 7.

It is seen that a wide scatter in the values of h/h_0 exists, but that the scatter decreases with increasing values of h_0 . In some experiments where the effective liquid height H_0 was kept constant while Q was increased in steps, a maximum pool height was observed to occur at $h_0 \approx 1.0$. This phenomenon of void fraction reduction with increasing vapor flux is similar to the well-known transition from "bubbly-flow" to "churn-turbulent flow" in experiments of injection of gases in liquid⁸. For $h_0 > 2.5$, significant water entrainment with the flowing vapor was observed.

The vapor volumetric rate of flow at any height relative to the volumetric flux of liquid-vapor mixture, $j_{v\ell}$, commonly been assumed to depend only on the planer void fraction, α ; i.e.

$$j_{v\ell} = \alpha(1-\alpha)^n V_\infty \quad (2)$$

Figure 1. Non-dimensional pool height variation with h_0 .

In equation (2), n is a regime-dependent constant. For a regime in which bubble interactions are low, $n > 1$. When significant bubble agglomeration and entrainment occurs, n is less than unity and is equal to zero for fully developed churn-turbulent flow. Based on equation (2), approximate relation between h and h_0 may be derived.⁶ The theoretical predictions for $n=1$ and $n=0$ are shown in Figure 1. It is seen that while there is a wide spread in the data, the minimum values of h/h_0 follow the trend of the $n=0$ line.

If the present results are extended to a boiling fuel pool at atmospheric pressure and with a specific boiling heat rate as low as 1% of the nominal operating power ($h_0 = 1.5$), the void fraction in the pool is expected to be 40% ($h/h_0 = 1.67$) or higher.

It should be emphasized, however, that the void fraction in an internally heated pool changes with the height in the pool. Shown in Figure 2 is a plot of the local void fraction versus height in the pool for Run 42. To obtain the void fraction, the actual pressure at a given depth is measured and is recorded on the plot as the millivolt output of the pressure transducer used. The measured pressure differential per unit height in the pool decreases with height due to the larger portion of vapor in the unit height. The pressure curve is then averaged by drawing a best fit curve and the void fraction is found from the slope of that curve using the proper conversion factor from millivolts to inches of pool fluid.

The surface of the boiling pool is defined as the intercept of the pressure curve with the pressure of the atmosphere. An integrated average void fraction may be found by summing the area under the void fraction curve to the defined height. A visually observed average boiling height was also measured, and is recorded in the graph. Knowledge of the visual boiling height and liquid height found after power shutoff provides an alternate method to calculate the average

Figure 2. Void fraction vertical profile in run 42.

void fraction. For Run 42, the calculated void fractions were 41% and 36% respectively for the pressure measurement integration method and the visual average boiling height method.

For a typical $\text{ZnSO}_4\text{-H}_2\text{O}$ solution used in the experiments, the surface tension is about 80% of the pure water value, a viscosity four to five times that of pure water at 100°C and a specific gravity of 1.05 to 1.1 at 100°C .

II.B. Heat Transfer To An Inclined Plate

The boron nitride and Lexan sheets necessary for construction of the inclined plate apparatus have been received. The boron nitride will be used as the heat transfer surface exposed to the boiling pool and the Lexan 1" plate will be used as the frame for the boron nitride and the container itself.

Plans presently call for the inclined plate surface to be made of alternating strips of boron nitride and Lexan as described in Reference 3. The bottom of the pool will consist of a solid 1/4" thick sheet of boron nitride backed up with sufficient cooling coils to insure a uniform and controlled temperature distribution. Temperature of the surface exposed to the boiling pool of the boron nitride will be found by integrating a matrix of thermocouples imbedded near the surface. The two sides of the boiling pool adjacent to the inclined test plate are copper electrodes which are necessary for heating of the pool, and the fourth side will be of Lexan to allow visual observation and an entrance for the makeup water.

A preliminary test of the bonding capabilities of Lexan to boron nitride will be performed to establish reliable techniques for the full scale experiment. While this testing is progressing the design will be finalized and initial construction initiated.

III. Flowing Fluid Streaming/Freezing Phenomena

The objective of the streaming/freezing experiments program is to study the process of freezing of a liquid in transient flow inside a cool cylindrical tube in order to:

- a) Define the conditions under which transient freezing may be controlled by "bulk-freezing" or by "radial freezing" concepts⁹, and
- b) Verify the models that have been developed for the transient freezing process.

To achieve the above objectives two series of experiments will be performed. In both experiments, molten fluid will be allowed to suddenly flow through a cooled tube. The wall temperature of the tube will be maintained at a temperature substantially below the freezing temperature of the flowing hot fluid.

III.A. Experiments With Non-Melting Channel Wall

III.A.1 Apparatus Description

A schematic view of the apparatus to be used is shown in Figure 6 of the previous report.³ The major experimental system consists of three parts:

- (1) a reservoir tank (14.6 cm I.D. x 21.3 cm height), (2) a test section (0.47 cm I.D. x 68.2 cm long and 1.11 cm I.D. x 68.8 cm long brass tube), and
- (3) a catch tank.

The reservoir tank is a cylindrical vessel where the molten fluid is stored at a controlled initial temperature and pressure. The two test sections that will be used in the present work are essentially single pass counter-current heat exchanger. Molten fluid flows through the inner tube which is cooled by water flowing vertically upward through the cooling-jacket formed by the space

between the concentric cylindrical tubes. The function of the catch tank (equipped with a sensitive load-cell at the bottom) is to receive and measure the transient flow rate of the fluid leaving the vertical test section.

III.A.2 Experiments with Paraffin Wax

As a part of the first series of experiments a total of 19 runs have been conducted using paraffin wax as a hot fluid. Test parameters and important results are summarized and shown in Table 1 (Test Conditions and Experimental Results).

As shown in Table 1, the runs are divided into four groups according to the major test parameters to be examined for their possible effects on the dynamics of the paraffin wax freezing process.

Group I : Effect of the initial paraffin wax temperature.

Group II : Effect of the coolant flow rate (i.e., the effective heat transfer coefficient external to the test section).

Group III: Effect of the pressure in the reservoir (i.e., effective driving pressure of the hot fluid).

Group IV : Effect of the flow channel diameter.

Typical results are shown in Figures 3 and 4. In Figure 3, the effect of initial fluid temperature on the paraffin wax displaced is shown and compared with the predictions of the model developed at BNL¹⁰ for the freezing process in cylindrical channels. The predictions of the model are in general agreement with the experimental results.

In Figure 4, the effect of driving pressure on the streaming rate is shown for different initial paraffin wax temperatures. Predictions of the model are also shown in Figure 4 with a solid line. From Figure 4, it may be observed that the amount of the fluid in the reservoir is extremely sensitive to the driving pressure for the case of the molten paraffin wax whose density is very small (the

Table 1. Test Conditions and Experimental Results

Group	TEST CONDITIONS							EXPERIMENTAL RESULTS	
	Run No.	Initial Paraffin Wax Temp. (°C)	Reservoir Pressure (atm.)	Coolant Flow Rate (gal/min)	Test Section I.D. (cm)	Coolant Temp. (°C)	Initial Head (cm)	Plugging Time (sec)	Total Mass Displaced(g)
I	1	55	1	5	0.47	15.6	13.9	22.5	34.6
	2	A 65	1	5	0.47	15.0	13.0	45.6	100.8
		B 65	1	5	0.47	13.9	14.4	53.2	151.5
	3	A 75	1	5	0.47	15.0	14.5	37.5	92.4
		B 75	1	5	0.47	13.9	14.5	38.3	86.8
		C 75	1	5	0.47	16.4	14.4	57.2	161.8
	4	A 85	1	5	0.47	15.8	14.5	311.9	----
		B 85	1	5	0.47	15.0	13.2	106.8	334.0
	5	A 95	1	5	0.47	15.0	14.7	399.7	1,396.0
		B 95	1	5	0.47	15.0	14.7	400.8	1,714.0
II	6	55	1	3	0.47	17.5	14.5	22.9	38.9
	7	65	1	3	0.47	13.9	14.7	28.3	55.0
	8	75	1	3	0.47	13.9	14.5	34.2	74.8
III	9	55	3	5	0.47	13.6	14.5	*54.4	1,603.9
	10	65	3	5	0.47	13.6	14.5	*31.2	1,726.6
	11	75	3	5	0.47	13.6	13.5	*27.0	1,606.8
IV	12	55	1	5	1.11	13.9	14.4	*30.9	1,607.9
	13	65	1	5	1.11	13.6	14.5	*28.6	1,616.4
	14	75	1	5	1.11	13.6	14.4	*24.2	1,609.0

*Time at which available mass ran out.

Figure 3. Mass of paraffin wax displaced through a 0.47 cm diameter channel as a function of flow time and fluid temperature.

Figure 4. Effect of driving pressure on streaming rate.

density of the paraffin wax is about 0.8 g/cm^3 at 25°C). The model of Reference 10 is in good agreement except for the case of the initial temperature of 55°C at 3 atm. pressure condition.

The effects of various parameters on the paraffin wax freezing process may be summarized as follows:

(1) Effect of the Initial Temperature:

- a. The plugging time increases as the initial molten fluid temperature level increases when other conditions are held constant. This observation is not surprising since one would expect that as the sensible heat of the molten fluid increases it will take longer to remove the sensible heat before freezing can begin to take place.
- b. Similarly, the total amount of fluid displaced through the channel prior to plugging increases as the molten fluid temperature level increases for the same conditions. This is mainly due to the following two reasons:
First, since the plugging time increases as the initial fluid temperature level increases the total flowing time increases resulting in the greater amount of displaced fluid.
Secondly, flow rate tends to increase as the temperature of the molten paraffin wax increases.

(2) Effect of the Coolant Flow Rate:

One would normally expect that the plugging time as well as the total amount of displaced fluid should increase as the coolant flow rate is reduced. However, as may be noticed in Table 1, the

effect of the reduction in the coolant flow rate (from 5 gal/min to 3 gal/min), on the freezing process is not appreciable. This may be attributable to the following facts:

In the present freezing experiment with the paraffin wax as a molten fluid, occasional wide variation in plugging time was noticed for similar test conditions. The primary reason for this occasional deviation, however, seems to be the degree of cleanliness of the inner surface of the test tube. Thus, there is a possibility that the effect of the coolant flow rate could easily be offset by the difference in the degree of cleanliness of the inner surface of the test tube. Also, it may be recalled that the thermal conductivity of the paraffin wax is extremely low ($0.00048 \sim 0.00053$ cal/cm-sec⁰C) which could, in effect, act as a thermal insulation (when its frozen layer thickness is appreciable) thereby reducing the effect of the change in the external heat transfer coefficient.

(3) Effect of the Pressure:

- a. It may be confirmed from the results of the tests at higher pressure conditions (Group III in Table 1) that the increase in the sensible heat of the molten fluid increases the flow rate thereby reducing the total time required to displace all of the initial charge of the molten fluid in the reservoir.
- b. Comparison of the terminal frozen layer thickness versus axial position along the test section shows that, in general, thickness at a given time and location is approximately inversely proportional to the fluid temperature. Also, the frozen layer becomes gradually thicker as the position along the wall moves axially downward for cases with sensible heat.

(4) Effect of the Diameter:

- a. The trend of the increase in flow rate at higher fluid temperature level was also confirmed from the experimental results of the group IV (where a larger test section I.D. was employed).
- b. It is obvious that longer time will be required to plug the larger test channel diameter for the same conditions.

III.A.3 Preliminary Results of the Tests with Wood's Metal

(1) Initial Temperature of Wood's Metal and Observed Type of Flow

In an effort to examine the effect of the type of fluid on the freezing process Wood's Metal has been tested at a temperature between 145°C and 75°C . The inside diameter of the test section for this test was 1.1 cm. Slug flow was observed at 145°C . However, when the initial temperature of Wood's Metal was lowered below 135°C a rivulet flow started to occur for the initial period of the transient flow.

(2) Pressurization and Slug Flow

In order to ensure a slug flow for every planned test the pressure in the reservoir was raised to 5 psig. A slug flow was observed from the early phase of the transient flow even at the temperature close to the freezing point of the Wood's Metal (i.e., 75°C).

Further tests will be carried out using various combinations of the test parameters to examine the effects of the parameters on the freezing process of the Wood's Metal.

IV. Delineation of Important Post-Accident Phenomena

IV.A. On The Downward Propagation Rate Of A Molten Heat-Generating Pool

In analysis of the consequences of a hypothetical meltdown accident for the LMFBR, it is important to estimate the rate of growth of a molten fuel pool into a solid material, such as ceramic beds of an ex-vessel core catcher or concrete floor. Melt-front propagation rates have often been determined⁽¹¹⁾ using heat transfer correlations obtained in experiments of volume-heated liquids with fixed boundaries. In such experiments^(12,13), the temperature controlled density gradient in the pool leads to a quiescent region near the bottom, thus hampering downward heat transfer.

For many situations of interest, the bed material is lighter than the fuel (e.g. MgO or CaO and SiO₂ concrete). Thus, the penetrating edge of the pool will be lighter than the bulk pool material, due to the higher concentration of the bed material. The actual density gradient will be governed by a complex interaction between the temperature and concentration profiles in the pool. Qualitatively, the density gradient due to the concentration profile stimulates instability of the pool near the bottom, thus enhancing downward heat transfer.

An approximate upper bound can be estimated for concentration-driven convection by noting that when the pool density gradient is dominated by component concentration effects, the density profile becomes similar to the bottom-heated, top-cooled pool. For this situation, the Nusselt number between the top and bottom is given by⁽¹⁴⁾

$$Nu_c = 0.069 (Pr)^{0.074} \left[\frac{gL^3 (\Delta\rho)}{\alpha\mu} \right]^{0.33} \quad (3)$$

where $\Delta\rho$ is the maximum density difference in the pool, L is the pool height, g is the gravitational constant, Pr is the Prandtl number, α is thermal diffusivity and μ is the viscosity of the pool material. In this limiting case, the fraction of heat that is transferred downward, for a horizontal layer, η_c , will be constant:

$$\eta_c = 0.5 \quad (4)$$

For a temperature-driven convection in a volume-heated layer, the fraction of heat transferred downward is given by⁽¹²⁾

$$\eta_T = \frac{1.43 R_I^{0.094}}{1.43 R_I^{0.094} + 0.33 R_I^{0.236}} \quad (5)$$

where

$$R_I = \frac{g\beta Q_V L^5}{\alpha^2 \mu c} \quad (6)$$

In the above equations, Q_V is the volumetric heat generation rate, β is the thermal expansion coefficient and c is the specific heat of the pool material.

Figure 5 shows the ratio (η_c/η_T) of the fractions of total heat that are transferred downward. It is seen that for the region of interest in applications, this ratio is between 4.5 and 8.5. In Figure 6, the ratio of the difference between the maximum temperature, T_p , and the boundary temperature, T_w , for both cases is shown. As seen in the concentration-driven convection case, the enhanced heat transfer leads to a decrease in T_p , for given total power and T_w .

Figure 5. Ratio of fraction of heat transferred downward for concentration-driven convection, η_c , to that for temperature-driven convection, η_T .

Figure 6. Ratio of temperature difference between the bulk and the bottom edge of the pool for concentration-driven convection to that for temperature-driven convection.

For a given total power, the rate of downward propagation is proportional to η . Therefore, propagation rate calculations based on temperature-driven convection will underestimate the downward propagation of a pool in a less dense material. This is in agreement with the experimentally observed⁽¹⁵⁾ increase in the downward melt-rate as density difference between the initial pool material and the bed material increases.

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