THERMOHYDRAULIC LMFBR SAFETY EXPERIMENTS

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JANUARY - MARCH 1976

M.S. KAZIMI, Principal Investigator

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FAST REACTOR SAFETY DIVISION
DEPARTMENT OF APPLIED SCIENCE
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TABLE OF CONTENTS

		<u>Page</u>
I.	INTRODUCTION	1
	I.A Scope of Work	3
	I.B Summary of Progress	3
II.	HEAT GENERATING BOILING POOL PHENOMENA	4
	II.A Experiment with Vertical Test Plate	4
	II.B Experiment with Inclined Test Plate	7
	II.C Phenomenological Modeling	11
III.	FLOWING-FLUID STREAMING/FREEZING PHENOMENA	14
	II.A Experiment with Non-Melting Channel Wall	15
	III.A.1 Apparatus Description	15
	III.A.2 Construction Progress to Date	15
	III.B Preliminary Results and Conclusions	17
	REFERENCES	21

LIST OF FIGURES

	<u>Page</u>
Figure 1: Schematic Diagram of the Boiling Pool Apparatus	5
Figure 2: Nusselt Number Measured in Preliminary Runs	8
Figure 3: Void Fraction Vertical Profile Measured in Preliminary Runs	8
Figure 4: Components of the Boiling Pool Apparatus with inclined Test Plate	9
Figure 5: Schematic view of the inclined Test Plate	9
Figure 6: Schematic Diagram of Apparatus Used in the Streaming Experiment	16
Figure 7: Effect of the Initial Paraffin Temperature on the Flow Rate	18
Figure 8: Effect of the Diameter of Flow Channel on Paraffin Displacement	18

LIST OF TABLES

Table 1: Comparison of Predicted α Values in a Boiling Pool of water	13
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NOMENCLATURE

a	an empirical constant
G_v'	heat generation rate per unit liquid volume
V	velocity
V_∞	terminal rise velocity of a bubble
y	vertical coordinate measured from bottom of the pool
α	void fraction
λ	heat of vaporization
ρ	density

Subscripts

v	vapor property
y	distance from pool bottom

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.

Summary of Progress

- 1.a. The apparatus of the boiling pool experiment has been modified to eliminate the oscillation in pressure of laboratory water supply system which affect the steady water make-up to the pool as well as cooling rate of the electrodes.
- 1.b. The static pressure measurement device has been installed. Thus, the vertical variation of the static head in the boiling pool can be inferred. This information will provide a means of estimating the vertical profile of the void fraction of the pool.
2. Several runs were performed in the streaming/freezing experiment using paraffin wax as a hot fluid. The preliminary information indicates that the initial temperature is an important parameter in determining the rate of solidification and time of plugging in a channel. Similarly, the driving pressure was found to significantly affect the rate of streaming and the potential for plugging in a channel.

II. Heat-Generating Boiling Pool Phenomena

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

II.A Experiment with Vertical Test Plate

II.A.1 Apparatus Description

The detailed description of the apparatus used in this experiment can be found in earlier reports^(1,2). The apparatus consists mainly of an open-top rectangular pyrex jar in which a water $ZnSO_4$ solution is brought to boiling by Joule heating. The electric current is supplied by two copper electrodes, which are cooled to suppress preferential boiling at the electrodes. The vertical variation of the heat transfer rate is to be measured using a segmented test plate placed between the two electrodes (see Figure 1).

Significant modifications of the apparatus have been made in this reporting period. Since the electric insulating coat of sprayed Teflon on the test plate had failed after a few runs, as mentioned in the last report⁽²⁾, a new insulating method is used now. A Teflon tape of about 0.003 inches thick with silicone based adhesive was applied to the plate. However, pre-heating of the tape was found necessary to eliminate gas evolution from the adhesive at the boiling

Figure 1. Schematic diagram of the boiling pool apparatus.

pool temperatures.

To determine the effective conductance of this tape, a calibration study was performed. A known heat flux was applied through a metallic heating block to the taped test plate. Measurement of the heating block temperature, as well as the aluminum surface temperature under the tape allows calculation of the heat transfer conductance across the Teflon tape.

To eliminate the problem of variable pressure in the laboratory water supply system, several methods were attempted. The method finally used was to feed the house water into a 50 gallon constant level tank, serving as the inlet to a centrifugal pump of a maximum capacity of 20 GPM at 85 psi head. The pump drives water through the cooling circuits. The rapid fluctuation of the pump pressure were easily damped through the installation of an air-water damper between the pump outlet and the cooling circuits.

The instruments used for measurement of the static pressure in the pool have been tested in a pool of water through which air bubbles are blown. These testing runs demonstrated feasibility of the method to determine the void fraction in the pool. This method relies on probing the differential pressure resulting from the vertical variation in the density of the pool due to the presence of the voids.

II.A.2 Preliminary Results

The parameters defining the extent of the boiling pool experimental investigation are listed as follows:

1. total pool height

2. specific liquid-volume heat generation rate, $\dot{G}_V$
3. test plate temperature

Representative data have been obtained for pool heights of 13, 18, 23 and 28 cm and specific heat generation rates from 0.087 to 1.36 cal/gm sec. Plate temperatures have been varied in the range from 66°C to 93°C with plate temperature distribution of up to $\pm 5^\circ\text{C}$, for any single run.

Figure 2 shows representative data for pool height of 23 cm and $\dot{G}_V$ of 0.212 cal/gm sec at an average surface temperature of 85°C. The experimental Nusselt number is compared to the Nusselt number calculated from the theoretical model for the same conditions. The model is described in Reference 2 and Section III.C of this report.

Figure 3 shows a void fraction traverse of a boiling pool of 23 cm height with $\dot{G}_V = 0.10$ cal/gm sec. The plot indicates a sharp void fraction jump at the point where the pool is visually separated into a bubbly regime and a foaming regime.

II.B Experiment with Inclined Test Plate

II.B.1 Design of the Experiment

The fundamental design for the inclined test plate experiment is completed. Three sides of the tank will consist of 1" thick Lexan bolted and bonded together. The test plate, which forms the fourth side, will be placed at fixed angles of 30°, and 45° from the vertical test plate apparatus, the electrodes will be perpendicular to the test plate and will be of a trapezoidal shape to allow uniform heat

Figure 2. Nusselt number measured in preliminary runs.

Figure 3. Void fraction vertical profile measured in preliminary runs.

Figure 4. Components of the boiling pool apparatus with inclined plate.

Figure 5. Schematic view of the inclined test plate.

generation throughout the pool. For each test plate angle a separate electrode set will not be necessary if the electrodes are extended in length and height to accommodate all configurations.

Figure 4 shows the components of the experimental apparatus set up for the 30° inclined test. The three vertical walls and the bottom of the tank are 1" thick Lexan sheets capable of withstanding the temperatures of boiling water, and are also transparent. The inclined wall used for all angles in the series of tests is a combination of Lexan and Boron Nitride. The Lexan forms a frame into which twelve Boron Nitride strips 5" by 3/4" by 1/4" thick are bonded on the surface facing the boiling fluid. (See Figure 5). A channel is cut in the Lexan behind each strip to allow flowing water to cool the inner surface of the strip.

Holes are drilled from the back of the Lexan frame into the center of the Boron Nitride to a depth 1/16" from the surface contacting the pool. The hole will allow a 1/16" diameter Chromel-Alumel thermocouple to be placed to measure the surface temperature after correcting for a temperature drop in the Boron Nitride material between the fluid and thermocouple junction.

Boron Nitride is a pressed composite which has anisotropic thermal conductivity. The thermal conductivity from the outer surface to the cooled inner surface is approximately 0.083 cal/sec cm⁰C while along the length of the strip the conductivity is approximately 0.041 cal/sec cm⁰C.

The significant advantage of this design is elimination of the thermal resistance between the test plate surface and the boiling pool. Because Boron Nitride has a high electric volume resistivity it is not necessary to insulate the test plate from the fluid.

II.C. Phenomenological Modeling

The correlation developed for predicting the heat transfer rate from a boiling pool in the churn-turbulent two phase regime has been reported on earlier⁽²⁾. The correlation requires a knowledge of the void fraction distribution in the pool. Based on the drift-flux co-current model of the two-phase flow, a prediction of the void fraction was made for the internally heated pool with constant volumetric heat generation. In reality, however, the heat generation will be uniform in the liquid phase only. Hence, an account should be taken of the void volume, where heating is negligible, when the amount of vapor generated at each horizontal plane is to be evaluated.

If $\hat{G}_V$ is the heat generation rate consumed in boiling per unit volume of the saturated liquid, we are interested in the vertical variation of the void fraction, α , under such conditions. In Reference 2, it was assumed that the superficial vapor velocity (in laboratory coordinates), V_V , may be related to the void fraction by:

$$V_V = \alpha(V_\infty + V_l) \quad (1)$$

where V_∞ is the terminal rise velocity of a bubble in a liquid and V_l is the effective up-flow velocity of the liquid due to vapor lift. Furthermore,

it was assumed that

$$V_1 = a \cdot \alpha \quad (2)$$

where a is a constant equal to $10V_\infty$.

By differentiating Equation (1) and making use of Equation (2), it is clear that

$$\frac{dV_v}{dy} = (V_\infty + 2a\alpha) \frac{d\alpha}{dy} \quad (3)$$

Here y is the vertical coordinate measured from the bottom of the pool. The superficial velocity gradient at any location, y , in the pool can be related to the boiling rate by:

$$\frac{dV_v}{dy} = \frac{G_v}{\lambda \rho_v} (1 - \alpha) \quad (4)$$

By equating the right hand terms in Equations (3) and (4) and carrying on the integration it can be seen that

$$\ln(1 - \alpha) = - \left[2a\alpha + \frac{G_v}{\lambda \rho_v} y \right] \frac{1}{V_\infty + 2a} \quad (5)$$

If it is assumed that

$$\ln(1 - \alpha) \approx -\alpha - \frac{\alpha^2}{2} \quad (6)$$

then the value of α may be obtained from:

$$\alpha = \frac{V_\infty}{V_\infty + 2a} \left[\left(1 + \frac{2G_v (V_\infty + 2a) y}{\lambda \rho_v V_\infty^2} \right)^{\frac{1}{2}} - 1 \right] \quad (7)$$

A simplification of the expression of α may be introduced if the expansion of $\ln(1-\alpha)$ is taken to be:

$$\ln(1-\alpha) \approx -1.2\alpha \quad (8)$$

The resulting expression of α in this case is:

$$\alpha = \frac{G'_V y}{\lambda \rho_V} \frac{1}{1.2V_\infty + 0.4a} \quad (9)$$

Equation (9) is compared to Equation (7) for various values of G'_V in Table 1.

Table 1

Comparison of Predicted α Values
In a Boiling Pool of Water*

G'_V (cal/cm ³ .sec)	α_1 (Eq.7)	α_2 (Eq.9)
.1	0.077	0.026
.3	0.157	0.080
.5	0.214	0.133
.7	0.257	0.187
.9	0.30	0.240

*The physical parameters used in the calculations are: $\lambda=540$ cal/g,
 $\rho_V=5.98 \times 10^{-4}$ g/cm³, $V_\infty = 22.5$ cm/sec and $y = 10$ cm.

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" concepts⁽³⁾, 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.

The effects of the following variables on the freezing process will be studied:

- 1) Type of fluid
- 2) Initial fluid temperature
- 3) Internal diameter of the tube
- 4) The heat transfer coefficient external to the tube
- 5) Pressure in the reservoir (i.e., effective driving pressure of the hot fluid)
- 6) Simultaneous melting of the cold wall

The first series of experiments will determine mainly the effect of the first five variables above. The second series of experiments will address variable (6) above.

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. 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 annular 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 Construction Progress to Date

Construction of the experimental apparatus has been completed. Instrumentations to monitor the temperatures of the molten fluid and coolant, the pressure in the reservoir, the coolant flow rate, and the transient flow rate of the molten fluid via a load-cell have been completed and calibrated.

Further effort will be focused on the completion of the remaining instrumentations, which include wall thermocouples to measure the

Figure 6. Schematic diagram of apparatus used in the streaming experiment.

transient wall temperatures of the test section, and final checkup.

III.B Preliminary Results and Conclusions

Preliminary runs have been performed using paraffin wax as a hot fluid. In these experiments the initial wax temperature was varied between 55°C and 95°C . Measurements were obtained for two test tube diameters (0.47 cm and 1.11 cm) as well as for two reservoir pressure conditions (1 atm and 3 atms). The cooling water flow rate was high enough to keep the water temperature in the jacket at about 15°C .

Typical results are shown in Figures 7 and 8. In Figure 7, the effect of initial fluid temperature on the fluid flow rate is shown. These results indicate that significant increase in the flow rate occurs as the sensible heat in the fluid increases. The predictions of a model developed at BNL⁽⁴⁾ for the freezing process in cylindrical channels are also shown in Figure 7. The predicted behavior is in general agreement with the experimental results. For the predictions shown in Figure 7, the melting point has been taken as 52°C which is close to the value obtained experimentally.

In Figure 8, the effect of a larger diameter of the test section is shown for different initial wax temperatures. It is clear that the amount of fluid in the reservoir is sensitive to the diameter of the flow section. Also, from Figure 8, it is clear that the model of Reference 4 is in good agreement with the experimental trend.

The observations from the experimental results may be briefly summarized as follows:

Figure 7. Effect of the initial paraffin wax temperature on the flow rate.

Figure 8. Effect of the diameter of flow channel on paraffin wax displacement.

- 1) The plugging time increases as the initial molten fluid temperature level increases when other conditions are held constant.
- 2) Similarly, the total amount of fluid displaced through the channel prior to plugging increases as the initial fluid temperature level increases for the same conditions.
- 3) Comparison of the flow rates between the tests at one atmospheric pressure and 3 atmospheres show that the flow rates at the latter condition are almost an order of magnitude higher than the other case. The increased flow rates at higher pressure conditions tend to increase the plugging time, if not to prevent the occurrence of plugging.
- 4) Comparison of the terminal frozen layer thickness versus axial position along the test section shows that, in general, thickness at a given time 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.
- 5) The experimental and theoretical transient flow rates as predicted by the model of Gasser and Kazimi (as well as the mass of fluid displaced through a single channel)

are relatively in good agreement at lower fluid temperature level and at earlier times. However, the deviation increases as the fluid temperature and the time increases. Occasionally, a 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.

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