GROWTH OF MOLTEN CORE DEBRIS POOLS IN CONCRETE

PROGRESS REPORT

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SYNOPSIS

The heat and mass transfer processes taking place in molten core debris/concrete systems have been experimentally investigated. Two types of experiments have been conducted. The first experiment simulates the growth of a molten debris pool in a composite sacrificial bed. This experiment models debris pool growth in an inner, low-melting point, sacrificial material zone followed by a melting attack on the concrete bed. The purpose of the inner zone is to quickly melt and dilute the debris pool so that its subsequent downward growth in the concrete may be slowed.

In the second experiment a two-layer immiscible liquid system is volumetrically heated and allowed to melt into a low-density gas-releasing solid bed which is miscible in the initially-higher-density bottom liquid. The solid melts, mixes with, and dilutes the bottom liquid pool until its density is lower than that of the top liquid. At this time pool inversion occurs and the immiscible liquid sinks to the bottom of the pool displacing the now lighter fuel-concrete simulant. This experiment is aimed at understanding the phenomena taking place in molten debris pools with an immiscible steel layer on top.

This report summarizes efforts made on this study during the three month period between April 1, 1979 and June 30, 1979. During this period, numerous test runs on both types of experiments have been conducted. For the first experiment, the results obtained so far indicate that composite sacrificial beds will be more effective in laterally containing the debris pool only if significant amounts of non-condensable gas are released by

the main bed material. For the second experiment, the results indicate that two-layer pools have a significantly different growth pattern than single-layer pools. For two-layer pools, shallower pools are obtained than single layer pools only when the gas release rate is low; the reverse is true for high gas release rates.

I. INTRODUCTION

I-A. Background and Overview of Present Study

An experimental investigation has been undertaken at the University of Wisconsin to examine the different heat and mass transfer processes taking place in molten core debris pools growing in concrete beds. The aim of this investigation is to develop the basic understanding and obtain the data base necessary for predicting the effects of the different physical parameters on the axial and radial growth rates of molten debris pools. Such information is needed to ascertain the efficacy of the third line of assurance for LMFBR safety.

During the previous contract period, two experiments were conducted [1]. The first was concerned mainly with heat transfer to the surfaces of a volumetrically heated pool with noncondensable gas injection at the boundaries. In the second experiment, the pool growth and gas release processes were coupled so that core debris/concrete systems could be closely simulated.

In the first experiment, the effects of gas injection rate, internal Rayleigh number, and pool aspect ratio on the relative downward, side-ward, and upward heat transfer rates have been investigated. The experimental apparatus consists of a rectangular test cell bounded from the sides and bottom by nearly-isothermal porous brass plates through which a non-condensable gas is injected at controlled rates. Joule heating of an electrolyte solution contained within the test cell provides the volumetric heat source and simulates the core debris pool. The upper pool boundary is either a free surface or an isothermal copper plate with

holes to allow passage of the injected gas out of the pool. Measurements of the pool temperature distribution along with the downward, sideward, and upward heat transfer rates have been made. A wide range of internal Rayleigh numbers, gas injection rates, and pool aspect ratios have been investigated. A total of 400 experiments have been made. Correlations for the downward, sideward, and upward Nusselt numbers have been obtained.

The data clearly shows that gas injection will markedly affect the heat transfer rates at the pool surfaces. The downward heat transfer rate is significantly increased with gas injection; values of f_{down} which are more than double the corresponding natural convection values have been observed (Fig. 1).

The pool maximum temperatures are considerably reduced with gas injection compared to natural convection values. The pools are well stirred by the gas and show nearly isothermal temperature distributions. Natural convection effects are found to be negligible in the gas mixed pool; the downward, sideward and upward Nusselt numbers are independent of the internal Rayleigh number (Fig. 2). Figure 3 shows variation of the reduced sideward and downward Nusselt numbers with gas velocity for pools with a cooled solid upper boundary. The Nusselt numbers are normalized by dividing them by their natural convection counterparts ($V_g = 0$). These results show that the downward Nusselt numbers are markedly increased by gas injection while the sideward Nusselt numbers are only moderately increased. For the case shown in Fig. 2, Nu_{down} increases to more than five times its natural convection value when the gas velocity is only 1.5 cm/min while the sideward Nusselt number increases by a factor of two.

Figure 1, Variation of the fraction of pool power removed at the lower boundary with superficial gas velocity.

Figure 2: Variation of the average Nusselt number along the bottom surface of the pool with internal Rayleigh number and aspect ratio for pools with a cooled solid upper boundary with and without gas injection.

Figure 3: Variation of the reduced sideward and downward average Nusselt numbers with gas velocity for pools with a cooled solid upper boundary.

The Nusselt numbers are found to depend on the product of Reynolds and Froude numbers; $(Re \times Fr) \equiv (\rho V^3 / \mu g)$, where ρ and μ are the density and viscosity of the pool, g is gravitational acceleration, and V is the superficial gas velocity. Typical results for pools with a free surface upper boundary are shown in Fig. 4.

The following Nusselt-type correlations have been obtained [3]. For pools with a solid upper boundary, the downward Nusselt number is given by:

$$(Nu_o) (W/L) = 204 [Re \times Fr]^{0.05} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-3}) \quad (1)$$

where $Nu_o \equiv h_o L / k$, h_o is the average heat transfer coefficient along the bottom surface of the pool, L is the pool depth, W is the pool width, and k is the thermal conductivity of the pool. For pools with a free upper surface, the downward Nusselt number is given by:

$$(Nu_o) (W/L) = 231 [Re \times Fr]^{0.074} \quad (10^{-10} \leq (ReFr) \leq 10^{-2}) \quad (2)$$

The sideward Nusselt number for pools with a solid upper boundary is given by:

$$(Nu_s) (W/L) = 194 [Re \times Fr]^{0.043} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-3}) \quad (3)$$

The upward Nusselt number for pools with a solid upper boundary is given by:

$$(Nu_1) (W/L) = 565 [Re \times Fr]^{0.048} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-2}) \quad (4)$$

Figure 4 : Variation of the Downward Nusselt Number with the Product of Reynolds and Froude Numbers for a Volumetrically-Heated Pool with Gas Injection at the Boundaries:

The above correlations can be used to predict the heat transfer rates along the surfaces of a volumetrically-heated pool with gas release at the boundaries over a wide range of the independent variable ($ReFr$). These results show that for pools with gas injection, the downward and sideward Nusselt numbers are comparable in contrast to the natural convection case where the sideward Nusselt numbers are significantly higher than those for the downward direction. The downward Nusselt number in a free upper surface model shows a higher dependence on the superficial gas velocity than models with a solid upper boundary. This underscores the importance of proper modelling of the boundary conditions in actual systems. The debris pool may have a stratified layer of molten steel on top with, possibly, a crust layer at the interface. Since concrete is miscible in UO_2 , the debris pool will be continually diluted to the point where its density becomes lower than that of the steel layer above. The inversion process that follows will significantly affect the heat and mass transfer rates at the pool boundaries. Understanding of such transient phenomena is necessary for accurate modelling of core debris behavior. Therefore, a large fraction of our effort this year has been devoted to the study of two-layer pools.

The growth of a volumetrically-heated pool in a miscible gas-releasing solid bed has been investigated [1]. Photographic techniques have been used to examine the effects of the gas release rate, pool/bed density ratio, pool power density and aspect ratio on the evolution of pool shape. A homogeneous mixture of Carbowax 1540 and ammonium bicarbonate (NH_4HCO_3) was used to simulate the concrete bed. The ammonium bicarbonate decomposes near the melting temperature of the wax releasing ammonia, carbon

Figure 5: Variation of the reduced pool height and width with time for volumetrically-heated pools of two different densities growing in gas-releasing miscible solid beds.

Figure 6: Variation of pool aspect ratio with time for volumetrically-heated pools of different power levels growing in miscible solid beds with no gas release.

Figure 7: Variation of the pool aspect ratio with time for volumetrically-heated pools of two different densities growing in gas-releasing miscible solid beds.

Figure 8: Variation of pool aspect ratio with time for volumetrically-heated pools growing in miscible solid beds with and without gas evolution.

dioxide, and water vapor. Different amounts of ammonium bicarbonate were mixed with the wax to obtain different gas release rates.

The results show that the pool height L initially increases at a faster rate than its width W . However, the rate of change of L with time gradually decreases until the trend is reversed (Fig. 5). The characteristic time at which the pool reaches a configuration of minimum aspect ratio is a function of the initial pool power density q_0 and is slightly affected by both the initial density ratio and the gas release rate (Figs. 6-8). The minimum aspect ratio $(W/L)_{\min}$ increases with the pool density ratio (ρ_p/ρ_b) , i.e. pools of higher initial density tend to penetrate deeper into the solid bed (Fig. 7). The minimum aspect ratio slightly decreases with increasing gas evolution rate (Fig. 8). Also, for times greater than $\tau_{\min}$ the depth of a gas releasing pool continues to grow at a rate nearly equal to that of the pool width whereas for pools with no gas release the pool depth increases at a much slower rate than its depth.

Based on the data obtained in [1], generalized correlations for estimating the radial and downward growth rates for pools with or without gas evolution have been developed [2]. For pools with no gas release the nondimensional downward and sideward penetration rates, $\dot{\mathcal{L}}$ and $\dot{\mathcal{W}}$, are given by:

$$\dot{\mathcal{L}} = 1.06 (Ra)^{-0.143} \left[\frac{\rho_p}{\rho_b} \right]^{3.62} (Pr)^{-0.419} (f_c)^{-2.35} \quad (5)$$

and

$$\dot{\mathcal{L}} / (\dot{\mathcal{L}} + \dot{\mathcal{W}}) = 1.82 (Ra)^{-0.062} \left[\frac{\rho_p}{\rho_b} \right]^{1.15} (Pr)^{-0.559} (f_c)^{-1.03} \quad (6)$$

where,

$$\left. \begin{aligned} 4.2 \times 10^6 &\leq Ra \leq 8.5 \times 10^8 \\ 0.94 &\leq \rho_p / \rho_b \leq 1.89 \\ 2.56 &\leq Pr \leq 9.07 \\ 1.34 &\leq W/L \leq 3.49 \end{aligned} \right\} \quad (7)$$

$$\dot{\mathcal{L}} \equiv WB\rho_b \lambda \left(\frac{\partial L}{\partial t} \right) / P \quad (8)$$

$$\dot{\mathcal{W}} \equiv LB\rho_b \lambda \left(\frac{\partial W}{\partial t} \right) / P \quad (9)$$

$$f_c \equiv [1 + 4(L/W)^2]^{-1} \quad (10)$$

The nondimensional penetration rates $\dot{\mathcal{L}}$ and $\dot{\mathcal{W}}$ are essentially measures of the fractions of pool power convected downwards and sideways respectively. Knowledge of these quantities as a function of the instantaneous values of the relevant nondimensional groups should be sufficient to determine how the maximum pool height and width will change with time. One can simply march ahead in time by continually updating the values of W , L , and the nondimensional groups.

For pools growing in miscible, gas-releasing solid beds, $\dot{\mathcal{L}}$ and $\dot{\mathcal{W}}$ are given by:

$$\dot{\mathcal{L}} = 0.017 (\Lambda)^{0.307} \left[\frac{\rho_p}{\rho_b} \right]^{3.53} (f_c)^{-0.444} \quad (11)$$

and

$$\frac{\dot{L}}{(\dot{L} + \dot{W})} = 120 (Ra)^{-0.108} (\Lambda)^{0.164} \left[\frac{\rho_p}{\rho_b} \right]^{0.808} (Pr)^{-0.300} (f_c)^{-0.978} \quad (12)$$

where $\Lambda \equiv V_g L / \alpha$ is the nondimensional superficial gas velocity.

$$\left. \begin{aligned} 3.1 \times 10^6 &\leq Ra \leq 9.3 \times 10^8 \\ 1.9 \times 10^2 &\leq \Lambda \leq 1.8 \times 10^3 \\ 0.96 &\leq \rho_p / \rho_b \leq 1.89 \\ 2.44 &\leq Pr \leq 14.3 \\ 1.99 &\leq W/L \leq 3.94 \end{aligned} \right\} \quad (13)$$

The physical properties in Eqs. (5), (6), (11), and (12) are evaluated at the melting temperature of the solid bed. These equations are the main results obtained so far. They can be used to determine the time evolution of the maximum pool height and width for pools with or without gas release at the boundaries.

Based on the results obtained so far, two experiments have been proposed. The first experiment deals with growing debris pools in composite solid beds. This experiment will model debris pool growth in an inner, low melting point sacrificial material zone followed by a melting attack on the concrete bed. The purpose of the inner zone is to quickly melt and dilute the debris pool so that its subsequent downward growth in the concrete is slowed. In the second experiment, a pool consisting of two immiscible layers will be used to simulate debris pools growing in concrete with a steel layer on top. The solid will melt, mix with, and

dilute the bottom liquid pool until its density is lower than that of the top liquid layer. At this time pool inversion will take place and the immiscible liquid will sink to the bottom of the pool displacing the now lighter fuel-concrete simulant. These two experiments are the subject of this investigation.

I-B. Summary of Progress

1. The test cell to be used for both experiments has been built and fully instrumented.
2. Numerous test runs on both experiments have been successfully completed.
3. Three reports summarizing the results of this work have been prepared and submitted for publication.
4. Correlations have been developed for the Nusselt numbers in molten debris pool/concrete systems.
5. Mr. Felde, a graduate student working on this project, has successfully completed his M.S. thesis on the heat transfer characteristics of volumetrically heated pools with gas injection at the boundaries.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The test cell used in both types of experiments is an upright rectangular box with inside dimensions of 7.5, 35.0, and 40.0 cm (Fig. 9). The front and back faces of the box are made of double-pane glass sheets while the sides and bottom are made of 1.25 cm thick plexiglas. Two vertical and one horizontal brass plates, 6.4 mm thick and 7.5 cm wide, are placed inside the box to form the sides and bottom of the (7.5 x 25 x 25) cm gas-releasing composite solid bed. The brass plates are covered with a thin layer of electrically-insulating Mylar film. Two (25 x 25) cm stainless steel screens are placed inside the box and held next to the glass faces. These serve as electrodes for the passage of alternating current through the growing pool.

In the first type of experiments, the composite solid bed is cased between the brass plates and the glass faces of the box. The high-melting temperature outer bed is made of a homogeneous mixture of Carbowax 1540 (m.p. = 45°C) or Carbowax 4000 (m.p. = 53°C) and ammonium bicarbonate (NH_4HCO_3). The inner low-melting zone is made of Carbowax 1000 (m.p. = 35°C). The ammonium bicarbonate decomposes when the wax melts releasing ammonia, carbon dioxide, and water vapor. Different amounts of ammonium bicarbonate are mixed with the wax to obtain different gas release rates. A rectangular cavity 7.5 cm wide and 2.5 cm high is formed in the solid bed to contain the volumetrically-heated liquid. An aqueous solution of potassium iodide and zinc bromide is used to simulate the core debris pool. Pools of different initial density and viscosity can be obtained by varying the concentrations of potassium iodide and zinc bromide in the

Figure 9: Schematic Diagram of the Test Cell

solution as described in [1,2].

A water-cooled copper plate, 6 mm thick is placed atop the solid bed and is mounted so that it remains in contact with the pool throughout the experiment. The plate is covered with a thin layer of electrically-insulating Mylar film. The plate contains 3 mm diameter holes placed on a 2.5 cm square pitch. The gas released by the inner solid bed leaves the test cell through these holes. Cooling water is passed through the plate so that near-isothermal conditions can be maintained. The water flow rate is measured by a rotameter while its inlet and exit temperatures are measured by copper-constantan thermocouples.

The entire test cell is covered by a 1.25 cm thick plexiglas plate positioned 2.5 cm above the copper plate. A glass-encapsulated copper constantan thermocouple probe penetrates the cover and is mounted so that it can be moved vertically along the pool centerline. The thermocouple output is measured by means of a digital thermometer.

Power is applied to the stainless steel electrodes in contact with the liquid pool. The power level is maintained constant throughout the experiment. When power is applied to the pool its temperature quickly rises to and beyond the melting temperature of the inner liner. As the wax melts the pool rapidly grows until the inner liner is all melted. At that time the pool temperature begins to rise again until it reaches the melting temperature of the main bed. When the main bed begins to melt, the ammonium bicarbonate decomposes releasing ammonia, carbon dioxide, and water vapor. The ammonia and the molten wax readily dissolve in the pool while the carbon dioxide bubbles through the pool

and is removed by means of an aspirator connected to the top of the test cell. A 35-mm camera is used to photograph the pool at regular intervals along the transient. The digital thermometer and a clock are placed near the test cell so that the time and pool temperature are recorded on each photograph. The pool dimensions are measured from the photographs by means of an optical comparator.

A listing of the composite bed experiments conducted in this investigation is given in Table 1.

The above described test cell has also been used in the second type of experiments where a two-layer pool is used. The solid bed is cast from a homogeneous mixture of Carbowax 1540 and ammonium bicarbonate. An aqueous solution of potassium iodide and zinc bromide is used to simulate the core debris pool. The overlaying steel layer is simulated using a 0.5 cm thick layer of 1-iodoheptane ($\text{CH}_3 (\text{CH}_2)_5 \text{CH}_2 \text{I}$) liquid ($\rho = 1.38 \text{ g/cc}$) or 1-bromoheptane ($\text{CH}_3 (\text{CH}_2)_6 \text{Br}$) ($\rho = 1.15 \text{ g/cc}$) depending on the pool density. The density of these fluids falls between the initial density of the electrolyte and the bed. They are immiscible in water so that they form a segregated layer which is initially lighter than the pool.

Power is applied to the pool and is maintained constant throughout the experiment. The pool temperature quickly rises to and beyond the melting temperature of the wax. The pool grows by melting the wax while gas is released by the decomposing ammonium bicarbonate. The molten wax and ammonia readily dissolve in the pool while the carbon dioxide bubbles through the pool and is removed through holes in the upper plate. For low gas release rates, the overlaying immiscible layer remains atop the

pool until its density exceeds that of the diluted pool. At that time it gradually slides down the sides of the pool and stabilizes at the bottom surface. For high gas release rates, the overlaying layer breaks up into droplets to allow passage of the gas bubble through the pool. The droplets remain afloat until their density exceeds that of the pool and gradually sink to the bottom surface.

A 35 mm camera is used to photograph the pool at regular intervals along the transient. The pool dimensions are measured from the photographs by means of an optical comparator. Experiments have been conducted at different values of power input, initial pool density, top layer density, and gas release rates.

TABLE 1
Listing of Composite Bed Experiments

Run #	Inner Wax	Outer Wax	Power (W)	Gas Release (cc/cc)	Pool Density* (g/cc)
1	↑	↑	50	↑	↑
2	↑	↑	100	↑	1.34
3	↑	↑	150	↑	↓
4	↑	↑	50	↑	↑
5	↑	↑	100	ZERO	1.63
6	↑	↑	150	↓	↓
7	↑	↑	50	↑	↑
8	↑	↑	100	↓	2.25
9	↑	↑	150	↓	↓
10	↑	↑	50	↑	↑
11	1000	1540	100	12	↑
12	↑	↑	150	↓	↑
13	↑	↑	50	↑	↑
14	↑	↑	100	24	1.63
15	↑	↑	150	↓	↑
16	↑	↑	50	↑	↑
17	↑	↑	100	48	↑
18	↓	↓	150	↓	↓

*Other physical properties of the pool are given in Table 2.

TABLE 1 (Contd.)
Listing of Composite Bed Experiments

Run #	Inner Wax	Outer Wax	Power (W)	Gas Release (cc/cc)	Pool Density* (g/cc)
19	↑ CARBOWAX 1000 ↓	↑ CARBOWAX 4000 ↓	50	↑	↑
20			100	12	
21			150	↓	
22			50	↑	
23			100	24	1.63
24			150	↓	
25			50	↑	
26			100	48	
27			150	↓	
28			50	↑	↑
29			100	12	1.34
30			150	↓	↓
31			50	↑	↑
32			100	24	1.63
33			150	↓	↓
34			50	↑	↑
35			100	48	2.25
36			150	↓	↓

*Other physical properties of the pool are given in Table 2.

TABLE 2

Initial Physical Properties of the Liquid Pool

Fluid #	<u>Composition</u>		Wt % KI in Water	Density (g/cc)	Heat Capacity (J/g°C)	Thermal Conductivity (W/m°K)	Viscosity [†] (10 ⁻³ Pa.S.)
	Vol % KI	Vol % ZnBr ₂ [*]					
1	100	0	34	1.34	2.58	0.48	0.89
2	100	0	56 ^{**}	1.63	1.66	0.40	0.89
3	20	80	56 ^{**}	2.25	1.00	0.60	9.6

* 75 wt % ZnBr₂ in water

** Saturated solution

† From reference [7].

III. RESULTS, DISCUSSION, AND CONCLUSIONS

III-A. Pool Growth in Composite Beds

The main idea behind using a composite bed with a low melting temperature zone inside the main high melting temperature bed is that the inner zone would quickly melt and dilute the pool so that further growth into the main bed would be slowed. Experiments have been conducted to examine the efficacy of this concept. The pool power density and initial density, as well as the bed composition and gas release rate have been varied over wide ranges [4].

Typical results showing the pool dimensions L and W , reduced by their initial values L_0 and W_0 , as functions of time for simple and composite beds without gas release are given in Fig. 10. These results show that initially the pool grows in the composite bed at a faster rate than in the simple bed until the inner, low-melting-temperature zone is completely melted. Beyond that point, the pool growth rates, as indicated by the slopes in Fig. 1, are nearly equal in both cases so that pools growing in composite beds will be larger than those in simple beds at all times during the transient. This result is reasonable since, for the same power input, the internal Rayleigh number which is the governing parameter for this system will always be larger for a pool growing in a composite bed than that for a simple bed so that the heat transfer rates to the pool boundaries would be increased.

Results similar to those shown in Fig. 10 for gas-releasing beds are given in Fig. 11. These results show that initially the pool grows in the composite bed faster than in the simple bed. However, after the inner zone is completely melted the pool growth rate in the composite

Figure 10: Variation of pool dimensions with time for simple and composite beds with no gas release (double arrow indicates melting of inner zone).

bed becomes slower than in the simple bed. These results are reasonable since for gas-releasing beds the heat transfer rates at the pool boundaries are independent of the internal Rayleigh number and depend primarily on the superficial gas velocity [3].

The transient temperature histories for pools growing in simple and composite beds with gas release are shown in Fig. 12. These results show that there is a slight difference between the two cases. In both cases, the pool is thoroughly mixed by the percolating noncondensable gases and is nearly isothermal. Similar results to those shown in Fig. 12 for pools with no gas release are given in Fig. 13. Again, there is a slight difference between the temperature histories of pools growing in simple and composite beds.

A plot of the relative aspect ratio of the bed, $(W/L)/(W_0/L_0)$, for both simple and composite beds with and without gas release is shown in Fig. 14. These results indicate that for simple beds, gas release has a significant effect on the evolution of pool shape; for the same power level and pool/bed density ratio, gas-releasing beds have a shallower pool than those with no gas release. The same effect is true for composite beds, however the differences between pools with and without gas release are much reduced (Fig. 14). These results also show that the critical time at which the minimum aspect ratio is reached is considerably reduced when composite beds are used.

Variations of the fraction of pool power removed at the upper surface of pools growing in simple and composite beds with and without gas release are shown in Fig. 15. These results show that for zero gas velocity, f_{upward} , is very low, being less than 5%. Higher values of

Figure 11: Variation of pool dimensions with time for simple and composite beds with gas release (double arrow indicates complete melting of inner zone).

Figure 12: Transient Temperature Histories for Pools Growing in Simple and Composite Beds with Gas Release

Figure 14: Variation of Relative Aspect Ratio with Time for Simple and Composite Beds with and without Gas Release.

Figure 15: Variations of the Upward Power Fraction with Time for Pools growing in Simple and Composite Beds with and without gas release.

f_{upward} are obtained in agreement with reference [3].

Based on the results obtained so far as exemplified in Figs. 10, and 11, it appears that composite sacrificial beds will be more effective in retaining the debris pool only if significant amounts of non-condensable gas are released by the main bed material.

III-B. Effect of Overlaying Steel Layers

Experiments have been conducted to examine the effect of an overlaying steel layer on the evolution of debris pool shape as it grows into concrete. Initially, an immiscible layer of molten steel may exist on top of the debris pool. As the pool is continually diluted by the dissolved concrete its density decreases so that inversion of the top steel layer may eventually take place. The pool power density, initial density, overlaying layer density, and gas release rate from the bed have been varied [5].

Typical results showing the pool dimensions L and W , reduced by their initial values L_0 and W_0 , as functions of time for pools with and without an overlaying immiscible layer are shown in Figs. 16 and 17. These results show that initially the pool grows faster in the downward direction. However, the rate of change of L with time decreases until the trend is reversed. The reduced aspect ratios corresponding to the results shown in Figs. 16 and 17 are plotted in Fig. 18.

The results shown in Figs. 16 - 18 indicate that two-layer pools have a significantly different growth pattern than single-layer pools. In all cases, the pool height initially increases at a faster rate than its width so that the pool aspect ratio decreases with time (Fig. 18). However, the rate of change of L with time gradually decreases until the

Figure 16: Variations of pool dimensions with time for pools with and without an overlaying immiscible layer growing in a miscible solid bed with no gas release.

Figure 17: Results similar to those in Figure 16 for pools growing in gas-releasing miscible solid beds.

Fig. 18: Variation of Pool Aspect Ratio With Time for Pools With and Without an Overlaying Immiscible Layer at Different Gas Release Rates. (Arrow indicates upper layer inversion point.)

trend is reversed. The critical time $\mathcal{T}^*$ at which the pool reaches its minimum aspect ratio is a function of power density, gas release rate, and pool/bed density ratio. For single-layer pools, the gas release rate has a significant effect on the pool growth pattern; shallower pools are obtained as the gas velocity is increased. Also, the critical time $\mathcal{T}^*$ decreases as the gas velocity is increased. On the other hand, for two-layer pools, the gas release rate has a minor effect on the pool growth pattern (Fig. 18). For low gas release rates, the point at which inversion of the upper immiscible layer takes place can be clearly identified. At that point the layer stabilizes at the bottom surface of the pool and the rate of change of aspect ratio decreases. For high gas release rates, the inversion point is not clearly identified (Fig. 18) since individual droplets, rather than a continuous layer, gradually sink to the bottom with little impact on the pool hydrodynamics.

Variations of pool temperature with time for pools with and without an overlaying immiscible layer are shown in Figs. 19 and 20. These results indicate there is little difference between the two cases. Variations of the corresponding upward power fractions are shown in Fig. 21. Again low values of f_{upward} are obtained when gas is not released from the bed. For gas-releasing beds f_{upward} increases with time and remains nearly constant around the inversion point.

Based on the results obtained so far we conclude that the presence of an initially-lighter immiscible layer of steel on top of the debris pool may have a significant effect on its growth pattern in the concrete support structure below the reactor. Deeper pools than those obtained with single-layer pools result when the gas release rate from the concrete is

Figure 19: Variation of pool temperature with time for pools with and without an overlaying immiscible layer.

Figure 20: Results Similar to those in Figure 19 for Pools growing in gas-releasing beds.

Figure 21: Variation of Upward power fraction with time for pools with or without and without an overlaying immiscible layer growing in miscible beds with and without gas release.

high. The reverse is true at low gas release rates approaching natural convection conditions.

IV. REFERENCES

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V. NOMENCLATURE

f_{down}	Fraction of pool power removed at lower boundary
f_{side}	Fraction of pool power removed at one side plate
g	Gravitational acceleration
k	Thermal conductivity
L	Pool height
M	Inverse non-dimensional pool temperature rise
Nu_{down}	Average Nusselt number along the pool bottom
Nu_{side}	Average Nusselt number along the pool sides
P	Total pool power (Watts)
q_o	Initial power density of the pool (W/cc)
Q	Volumetric heat generation rate
Ra_{int}	Internal Rayleigh number; $Ra_{int} = g\beta QL^5/64\alpha\nu k$
Ra_{ext}	External Rayleigh number; $Ra_{ext} = g\beta L^3(T_{bot}-T_{top})/8\alpha\nu$
T_{bot}	Bottom surface temperature
T_{top}	Top surface temperature
T_{max}	Maximum pool temperature
ΔT	Pool temperature rise; $T = T_{max} - 0.5(T_{top} + T_{bot})$
$\dot{V}_g$	Superficial gas velocity
V_g	Gas release rate (cm^3 of gas per cm^3 of the bed)
W	Pool width
α	Thermal Diffusivity
β	Coefficient of thermal expansion
ν	Kinematic viscosity
ρ_b	Bed density
ρ_p	Pool density