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OUTLET PLENUM FLOW STRATIFICATION STUDIES FOR THE CLINCH RIVER BREEDER REACTOR PLANT

by

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ABSTRACT

The transient temperature behavior during a simulated reactor trip was studied in a 1/3 sector, 0.55 scale model of the reactor outlet plenum of the CRBRP. Buoyancy effects were simulated using water and salt solution. Effects of variations in Richardson Number (ratio of buoyancy/inertia forces) and Froude Number (ratio of inertia/viscous forces) were evaluated. Effects of geometrical changes of a component in the outlet plenum called the Upper Internals Structure on transient temperature response were studied; both height of the structure and leakage under this component were experimentally varied. The test results confirm that flow stratification occurs in the outlet plenum following a reactor trip. The colder, denser fluid issuing from the core assemblies during the transient fills the lower por of the plenum while the hotter fluid is trapped in the region above the ou.let nozzles.

INTRODUCTION

Design of reactor components exposed to flowing sodium in the Clinch River Breeder Reactor Plant (CRBRP) requires an accurate assessment of thermal transients caused by a reactor trip. The components most affected by a reactor trip, which is a sudden reduction in power due to insertion of control rods, are those located in the reactor outlet plenum and hot leg equipment downstream of the reactor vessel outlet nozzle.

A reactor trip results in a rapid reduction in temperature (approximately 300°F [167°C] in 20 seconds) of the sodium entering the outlet plenum from the fuel assemblies. The radial blanket exit sodium temperature also decreases, but at a slower rate. A reduction in total reactor flow rate (100% to 10% in 35 seconds) occurs simultaneously to minimize the rate of temperature change in the outlet plenum. The fuel and blanket temperature profiles and the flow coastdown curve are shown in Figure 1. During the initial portion of a reactor trip transient, the colder, more dense sodium does not have sufficient kinetic energy to overcome the negative buoyant forces and flow stratification occurs. This phenomenon was observed qualitatively in 1/10 scale model studies performed by Combustion Engineering[1]* in support of the Fast Flux Test Facility (FFTF) design. Subsequent studies, which provided quantitative data for FFTF, were performed by Carr and Flannigan at Battelle-Columbus Laboratory (BCL)[2] in a 1/3 sector

*Parenthetical numbers refer to references

0.55 scale model, and by Lorenz at Argonne National Laboratory[3] in a 1/15 scale model. These tests confirmed the presence of flow stratification.

The CRBRP reactor outlet plenum region is shown in Figure 2. The coolant exiting the core assemblies is ducted through the Upper Internals Structure (UIS) chimneys and enters the upper region of the outlet plenum. The outlet plenum, including the UIS, was modeled at Battelle by modifying the 0.55 scale model of FFTF described in Reference 2. This paper briefly describes the model and the test facility and summarizes the evaluation of the significant data. Additional details of the test and results can be found in References 4 and 5.

One function of the UIS is to reduce the severity of the temperature transient following a reactor trip, particularly at the outlet nozzle, by increasing plenum mixing. This is accomplished by directing the majority of the colder sodium, following a trip, into the hotter fluid still residing in the outlet plenum. In the test described in this paper, the transient temperatures and flow patterns resulting from negatively buoyant forces were simulated using water and a more dense salt solution. A temperature difference between the supply fluids was used as a tracer to determine the mixing characteristics. Subsequent sections of this paper describe the effects of variations of the UIS geometry and dimensionless parameters on the outlet plenum transient response.

Lorenz[3] concluded that model size effects are insignificant and that, for small scale models, water data conservatively predicts the transient response compared to sodium data. He also argues that for full scale plenum, the agreement between water and sodium transients will be even better. Therefore, the data obtained in this experiment should reasonably simulate full scale CRBRP sodium temperature responses in the outlet plenum.

EXPERIMENTAL INVESTIGATION

Model to Prototype Similarity

The extent of mixing that takes place in the reactor outlet plenum following a reactor trip and the resulting transient temperature responses, are determined by geometric configuration, fluid velocities, and fluid density differences. Modeling of plenum mixing requires that the flow model accurately reproduce the flow conditions which will exist in the reactor, i.e., that dynamic similarity be achieved. Dynamic similarity between a model and its prototype is achieved when the forces acting on similar volume elements have the same ratio. The fluid forces pertinent to this study are inertia, viscosity, buoyancy, and gravity from which the following three dimensionless ratios can be derived:

$$N_{Re} = \frac{\rho V D}{\mu} \quad \text{[Eq. 1]}$$

$$N_{Ri} = \frac{g D \Delta\rho}{\rho V^2} \quad \text{[Eq. 2]}$$

$$N_{Fr} = \frac{V^2}{g D} \quad \text{[Eq. 3]}$$

where

N_{Re} = Reynolds number, ratio of inertia/viscous forces

N_{Ri} = Richardson number, ratio of buoyancy/inertia forces

N_{Fr} = Froude number, ratio of inertia/gravitational forces

ρ = fluid density

V = fluid velocity

D = characteristic dimension (outlet plenum diameter)

μ = fluid viscosity

$\Delta\rho$ = difference in density between the two fluids (hot and cold sodium in the prototype; water and salt solution in the model)

g = gravitational acceleration

Only two of the above dimensionless ratios are independent since the Froude number is embodied in th[illegible] [illegible]dson number. Thus, duplication of the prototype Reynolds and Richar[illegible] [illegible]mbers in the model would result in dynamic similarity and the flow patterns in the prototype during a normal scram transient would be duplicated in the model. This could not be achieved in other than a 1:1 scale model. However, experience has shown that when the Reynold's number is greater than about 10,000, fluid behavior becomes relatively independent of Reynold's number. Therefore, the model was designed to allow matching of Richardson number while maintaining a Reynolds number well above 10,000.

Facility and Model Description

Figure 3 shows a schematic diagram of the experimental facility. A 1/3 sector model of 0.55 geometric scale was selected for the tests because the outlet plenum and upper internals structure exhibited 120 degree symmetry. The flow system consisted of two loops representing fuel assembly and radial blanket flow having maximum model flowrates of 8400 gpm and 1260 gpm, respectively. Each loop could be supplied from a fresh water tank or from separate , more dense, salt solution tanks. The system could be operated in a closed loop mode with the model effluent being returned to the fresh water tank or in an open loop mode with the effluent diverted into the recovery tank. The mixing valves for the fuel assembly flow and the two flow control valves were hydraulically operated and utilized controls to vary the closure rates. A manually operated delay between activation of the mixing valves and the flow control valves was provided to compensate for fluid transit time in the inlet piping.

The essential features of the geometrically scaled model are shown in Figure 4. The simulated Upper Internals Structure (UIS) was segmented so that the upper portion could be removed to study the effect of chimney height on plenum mixing. Flow entered the model through a core plate, which simulated exit flow from individual fuel and radial blanket assemblies. The collector plenum beneath the UIS was simulated including a baffle to separate fuel assembly flow from combined fuel assembly/blanket region flow. A sliding gate leakage control ring was installed to study the effects of clearance between the UIS and the top of the simulated core on plenum stratification.

Facility Operation

Following a reactor trip from steady state operation, thermal transients occur in the outlet plenum due to the changes in the core exit temperature and flow conditions which are shown in Figure 1. The temperature and flow transients simulated in the experimental model were approximations of the prototype behavior. The test inlet temperature profile consisted of a steep ramp down from the steady state temperature to a temperature near the initial minimum value followed by a hold at this temperature. The flow coastdown was simulated by a two step ramp down to the shutdown flow rate.

In the reactor, the sodium density increases by 4.3 percent as a result of the temperature transient. Changes in fluid density were simulated in the model by using three different supply fluids with densities adjusted , by adding salt, to obtain Richardson number simulation. To quantitatively measure the degree of mixing taking place in the model, the supply fluids were maintained at different temperatures selected to provide a linear relationship between the fluid temperature and density.

Model temperatures were measured with thermistors and fast response thermocouples. Bulk fluid tank temperatures were measured with precision mercury-glass thermometers just prior to the transient test and following a period of air agitation to promote mixing. A total of 34 thermistors and 31 thermocouples were installed in the model. All of the thermistor channels and 18 thermocouples could be monitored during any given test. Monitored thermocouples were selected based on the particular test being conducted and the model region of interest. Specific gravities of the tank solutions were measured with a hydrometer and adjusted to the specified values by adding salt or fresh water as required prior to each test run.

The thermistor circuits were connected to a data acquisition system u[illegible]zing a Hewlett-Packard Model 2100A central processor. The thermistor volt[illegible] were scanned and recorded at the rate of approximately two scans per seco[illegible] Thermocouple temperature measurements were recorded continuously on [illegible]rip-chart recorders and a 10 channel light beam strip-chart oscillograph. The synchronization of the various recorders and the HP acquisition system to transient test events was accomplished through the use of chart timing marks and stopwatches.

A typical reactor trip transient simulation was conducted in the following manner; steady state flow patterns were established in the model using recirculating freshwater in the fuel assembly and radial blanket loops. Shortly before the initiation of the transient simulation, the radial blanket loop feed was switched to a salt solution mixture representing the radial blanket steady state sodium temperature and density. Full flow was continued until nearly steady state conditions were established in the plenum at which time the fuel assembly flow loop was switched to its salt solution, the outflow from the model was diverted to the recovery tank and the flow coastdown was initiated. Initiation of the flow coastdown was timed to coincide with the entry of the salt solution into the model.

DISCUSSION OF TEST RESULTS

The experimental temperature responses to the simulated reactor trip are presented in normalized form in which the temperature changes during the transient are given as fractions of the inlet fluid temperature change.

A normalized temperature of unity corresponds to the steady flow fuel assembly inlet temperature and a normalized temperature of zero is equal to the temperature of the fuel assembly inlet fluid at the end of the transient. To facilitate the discussion of results, the temperature response curves are referenced to measurement locations identified on Figure 4.

Evidence of Flow Stratification

Flow stratification in the outlet plenum during a reactor trip transient was clearly demonstrated by the temperature response in the upper region of the plenum. Figure 5 shows the transient temperature response measured at five locations along a vertical traverse above the Upper Internals Structure (UIS). These temperature profiles illustrate the development of fluid strata above the UIS chimneys during a typical transient. At location A, near the top of the plenum, the response to the transient was slight indicating that the colder inlet fluid did not reach that location throughout the test. At locations B and C, the temperatures decreased by 40% and 65% of the inlet fluid temperature change, ΔT_o, shortly after initiation of the transient and then returned to and held substantially higher temperature levels for the remainder of the test, indicating the development and maintenance of fluid strata. At locations D and E, located close to the top of the chimneys, the temperatures decreased by 65% of the inlet fluid temperature change at 60 seconds after transient initiation. Temperature oscillations occurred at both of these locations for the test duration, indicating the existence of a fluctuating hot-cold fluid interface.

Further evidence of fluid stratification was observed at the top of the test model which simulates the entrainment suppressor plate in the reactor. Figure 6 shows the transient response from the outer edge to the center of the suppressor plate. The suppressor plate center location displayed the largest transient temperature response. The depth and duration of response decreased with increasing radius. From about 30 seconds after transient initiation until the end of the test, temperatures at the three suppressor plate locations nearly coincide, indicating a stratum of high temperature fluid existed across the bottom of the plate.

Effect of Leakage Gap

One of the design parameters of the UIS which can affect the outlet plenum transient is the size of the leakage gap beneath the skirt of the UIS collector plenum. Tests were made with gap sizes ranging from zero to nearly four times the prototypic dimension by adjusting the leakage control ring shown in Figure 4. The effect of gap size on the temperature response at the outlet nozzle is shown in Figure 7. The temperature response at the outlet nozzle was slowest for the test with the nominal gap. Both smaller and larger gaps resulted in faster transients at the outlet nozzle. This comparison indicates that the nominal gap size may be nearly optimum insofar as limiting the severity of the transient at the outlet nozzle is concerned. This behavior can possibly be explained by considering the flow paths taken by the fluid from the UIS collector plenum to the outlet nozzles. There are two alternate flow paths; one up the chimneys, then radially outward and down toward the nozzles and the other through the gap beneath the UIS, radially outward and up toward the nozzles. When the flow is evenly divided between these flow paths, the transit time to reach the outlet nozzle is longer than if the bulk of the fluid followed either path, and it is reasonable to assume that more mixing occurs when the flow paths are diverse.

The effect of gap size on the temperature response above the UIS is also shown in Figure 7. The test with the nominal gap resulted in the smallest temperature change and greatest degree of stratification in the region above the UIS.

Effect of Chimney Height

The height of the chimneys in the UIS is another design parameter which can affect the outlet plenum transients. The tall chimney design is based on the premise that forcing the cooler, transient fluid to enter the outlet plenum at a high elevation will cause the fluid to follow a longer flow path and, consequently, will involve a larger fraction of the plenum volume in the mixing process. One test was run with short chimneys (approximately one half nominal height) for comparison with the basic design. The effect of chimney height on outlet plenum transients is shown in Figure 8. At the outlet nozzle, the temperature response is faster for the short chimneys demonstrating that the tall chimney design provides some mitigation of the outlet nozzle transients. At location F, in the upper plenum region (see Figure 4), the temperature response is almost identical for both chimney heights for the first 50 seconds. After that, the temperature for the tall chimneys begins to decrease while the stratification persists for the short chimney test.

Effect of Richardson Number

The Richardson Number (see Eq. 2) is one of the dimensionless ratios which governs the dynamic simulation between the prototype and the test model. For most of the test runs ,the Richardson Number was simulated exactly by adjusting the model density change ($\Delta\rho/\rho$) to compensate for geometric scale and velocity differences between the model and the reactor. To study the effect of Richardson number on the plenum mixing characteristics, tests were performed at 0.5 and 1.5 of the nominal Richardson number by varying the relative density change, $\Delta\rho/\rho$. The results of these tests are compared to the standard test results in Figure 9. The normalized temperature response at the outlet nozzle is very similar for all three tests. At a location above the UIS, it is observed that the degree of stratification increases with increasing Richardson number.

Effect of Froude Number

At the maximum facility flow rate, the prototype velocities were simulated exactly. The corresponding Froude number ratio (model/reactor) was 1.84. To study the effect of Froude number on the flow and mixing characteristics in the outlet plenum, one run was made at a reduced flow (74% of full flow) in which the Froude number ratio equalled 1.0. The results of this test are compared to the results for the basic test condition in Figure 10. The temperature response at the outlet nozzle is more rapid for the reduced flow test (N_{Fr} = 1.0) than for the basic test condition. Also, the degree of stratification is less for the test with the lower Froude number, as demonstrated by the temperature response at location F above the UIS.

SUMMARY

Testing in a 0.55 scale model, using water and a salt solution to simulate density changes, demonstrated that flow stratification in the outlet plenum of the Clinch River Breeder Reactor will occur following a reactor trip. During the majority of the transients, a hot layer of sodium existed at the top of the outlet plenum.

Geometric changes in the UIS were evaluated in the test. Data illustrated that the prototypic gap beneath the skirt of the UIS produces a transient at the outlet nozzle which appears to have the least severe temperature rate of change compared to other gap sizes. Additionally, the data indicated that the transients at the outlet nozzle are more severe when the chimney height of the UIS is reduced.

Dimensionless parameters were experimentally varied and transient data were obtained. Normalized temperature transients at the outlet nozzle were similar for Richardson number ratios of 0.5 to 1.5 but more stratification occurred in the outlet plenum with increasing Richardson number. Temperature transients at the outlet nozzle were more severe and the degree of stratification was greater at reduced Froude number testing.

ACKNOWLEDGEMENT

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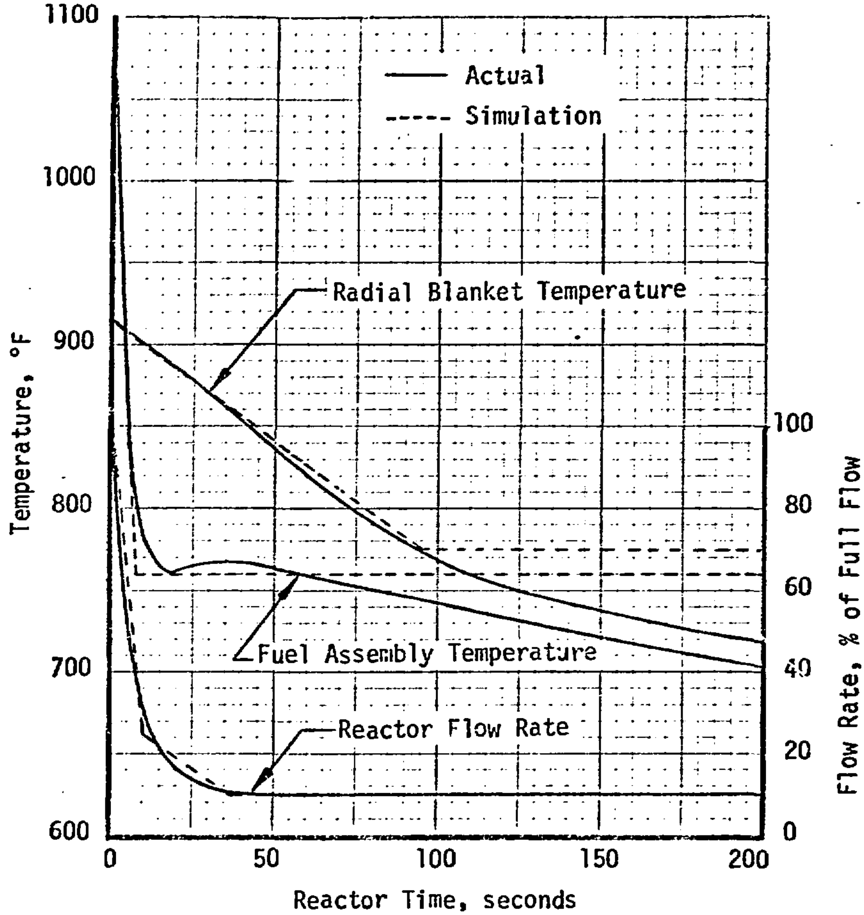

FIGURE 1

Prototype Fuel and Radial Blanket Exit Temperatures and Flow Rate During Reactor Trip Transient

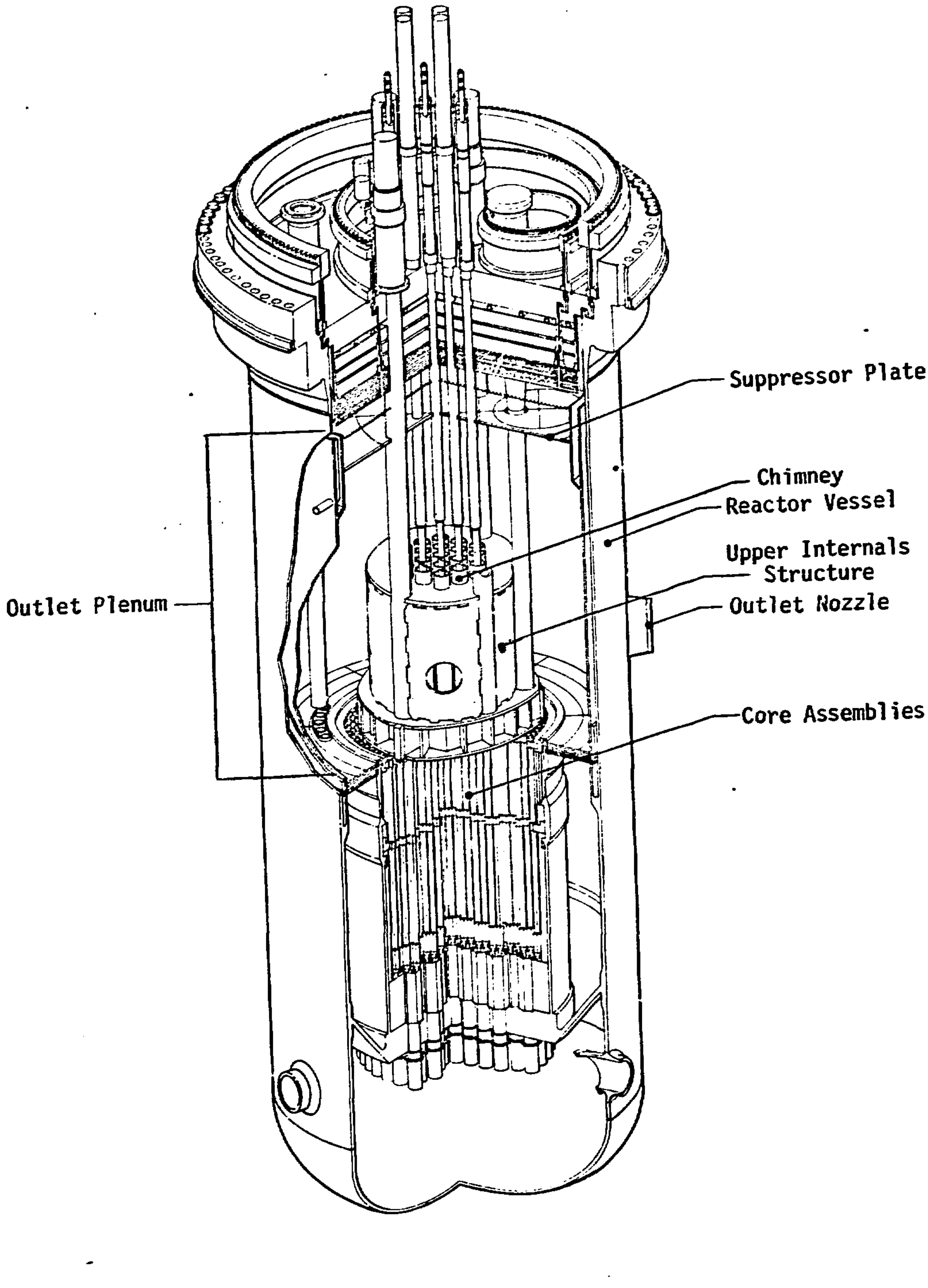

FIGURE 2

CRBRP Reactor Cutaway

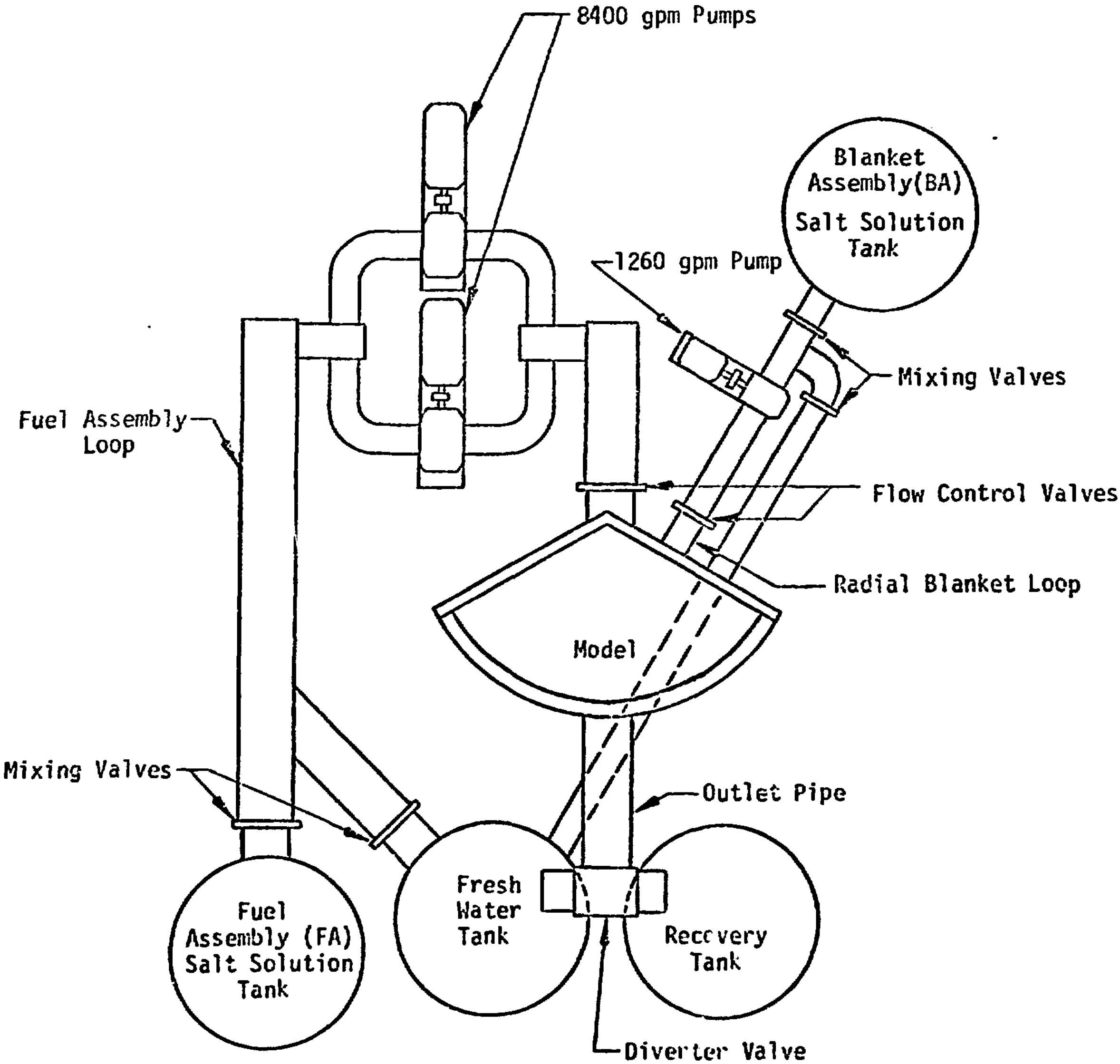

FIGURE 3

Schematic Diagram of CRBRP Outlet Plenum Flow Stratification Test Facility

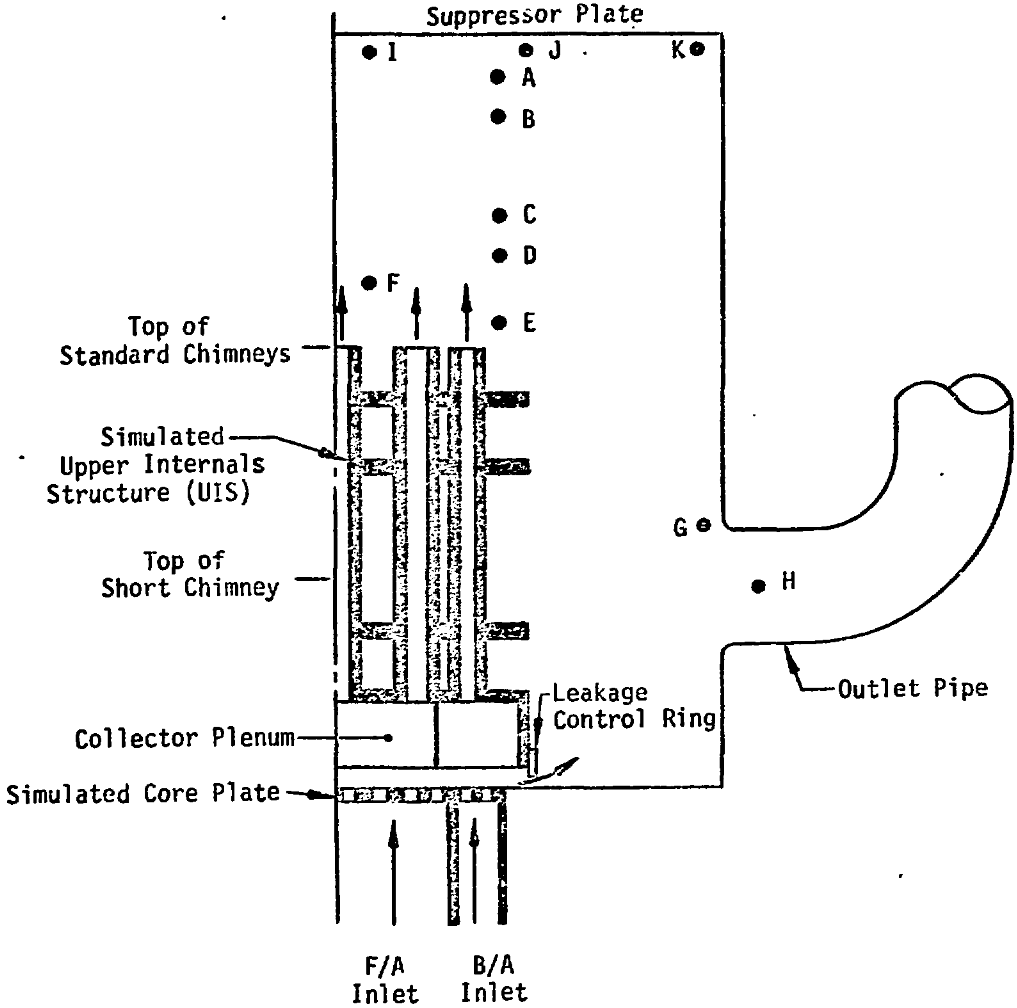

FIGURE 4

Elevation View of CRBRP Outlet Plenum Model
(Measurement locations discussed in text identified by letters A-K)

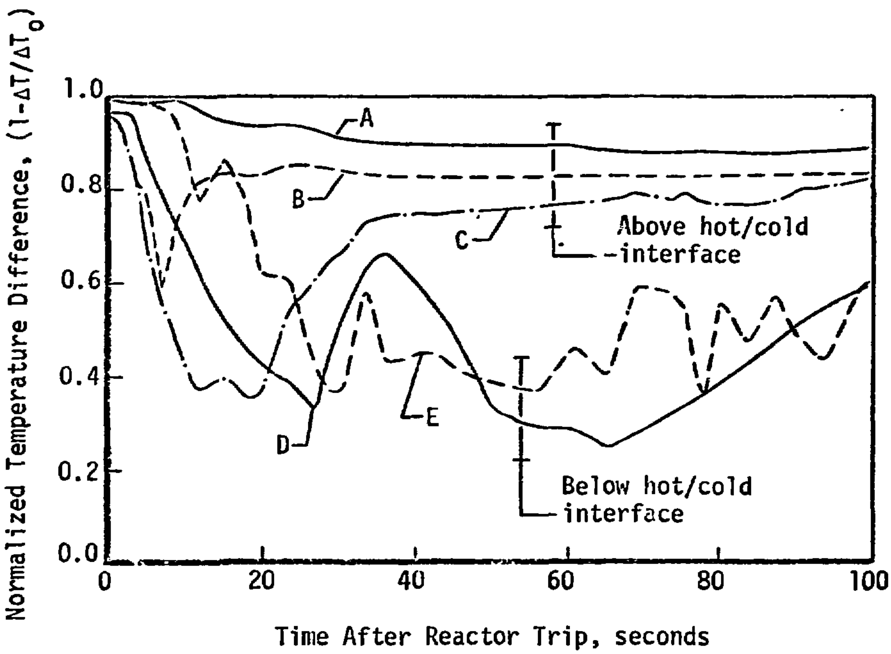

FIGURE 5. Formation of Hot/Cold Interface (Temperature response along vertical traverse above UIS; measurement locations identified on Figure 4)

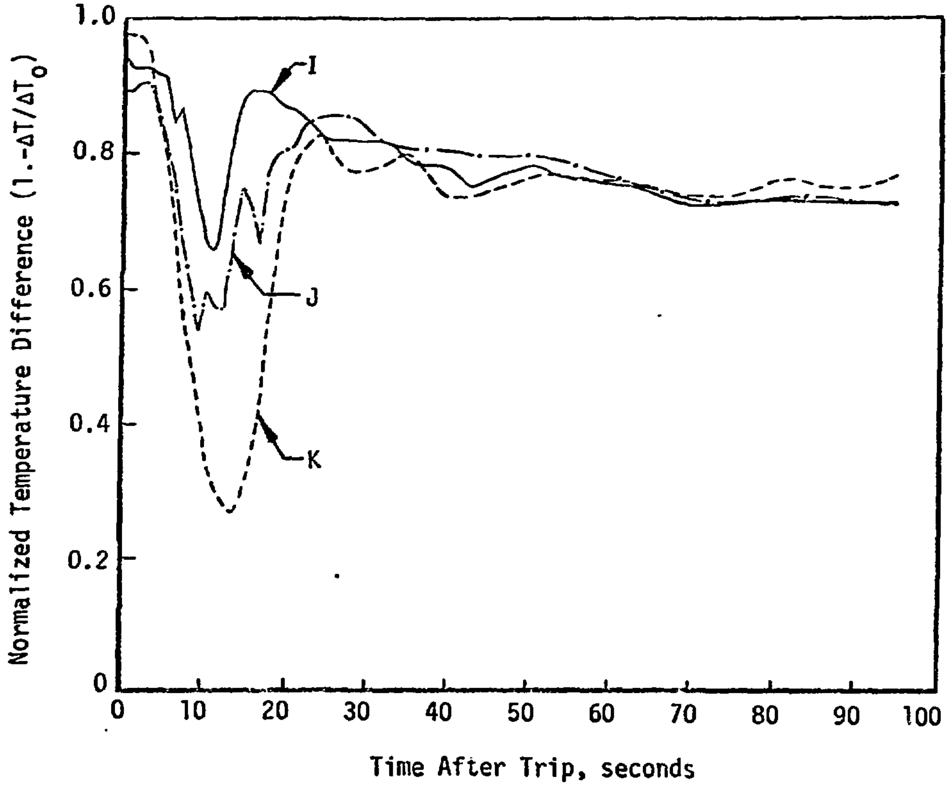

FIGURE 6

Normalized Temperature Response at the Suppressor Plate

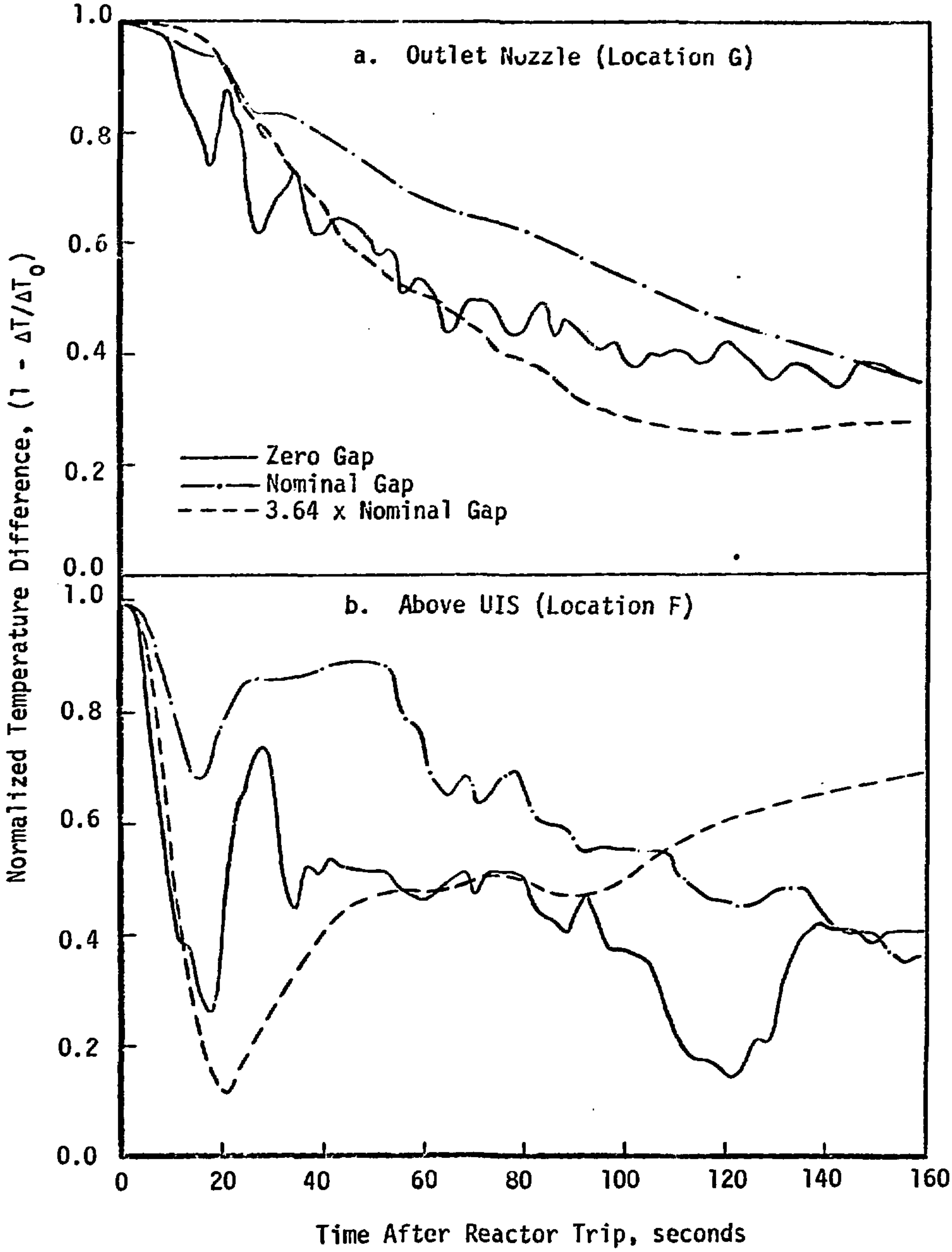

FIGURE 7. Effect of UIS Leakage Gap Size

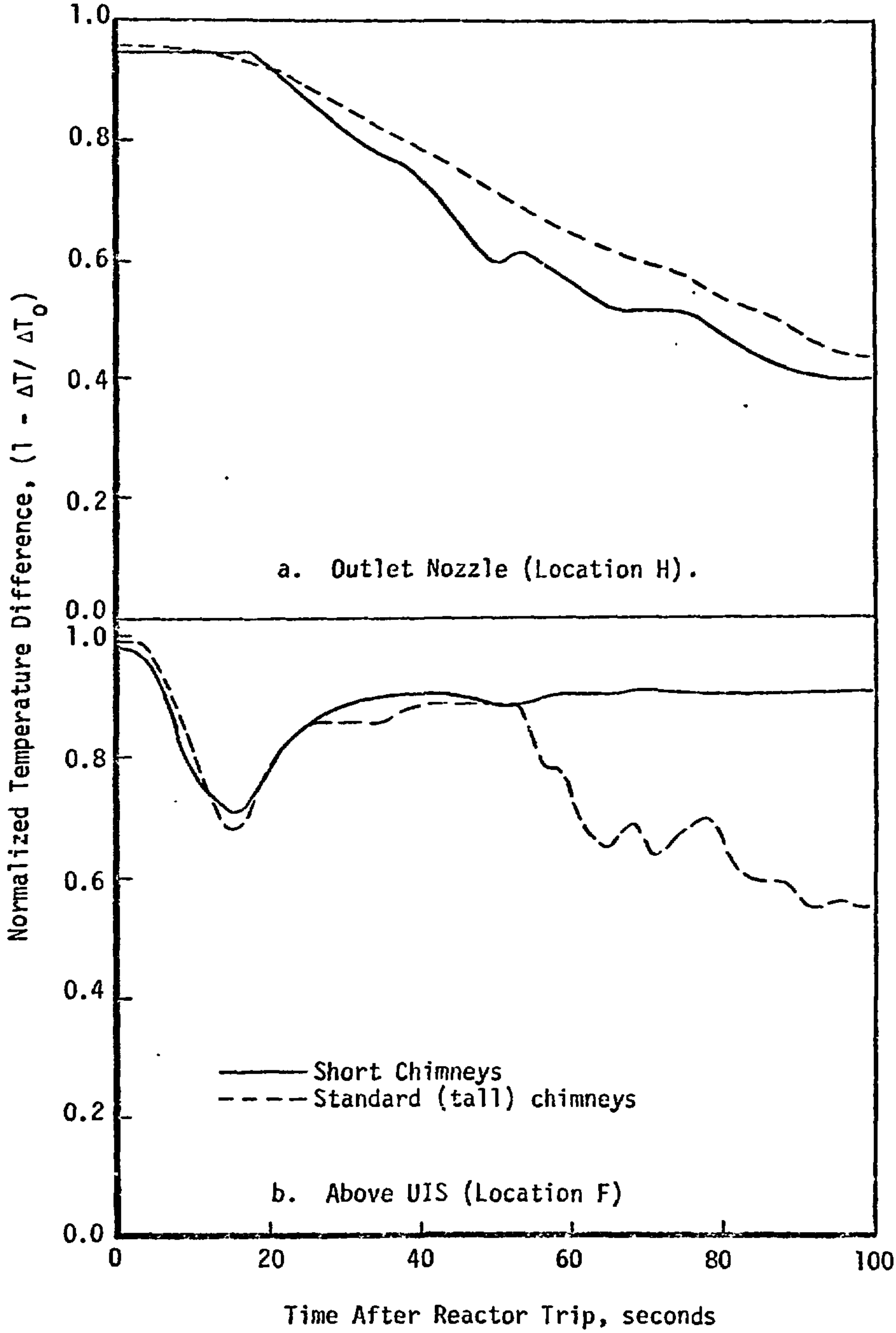

FIGURE 8. Effect of UIS Chimney Height

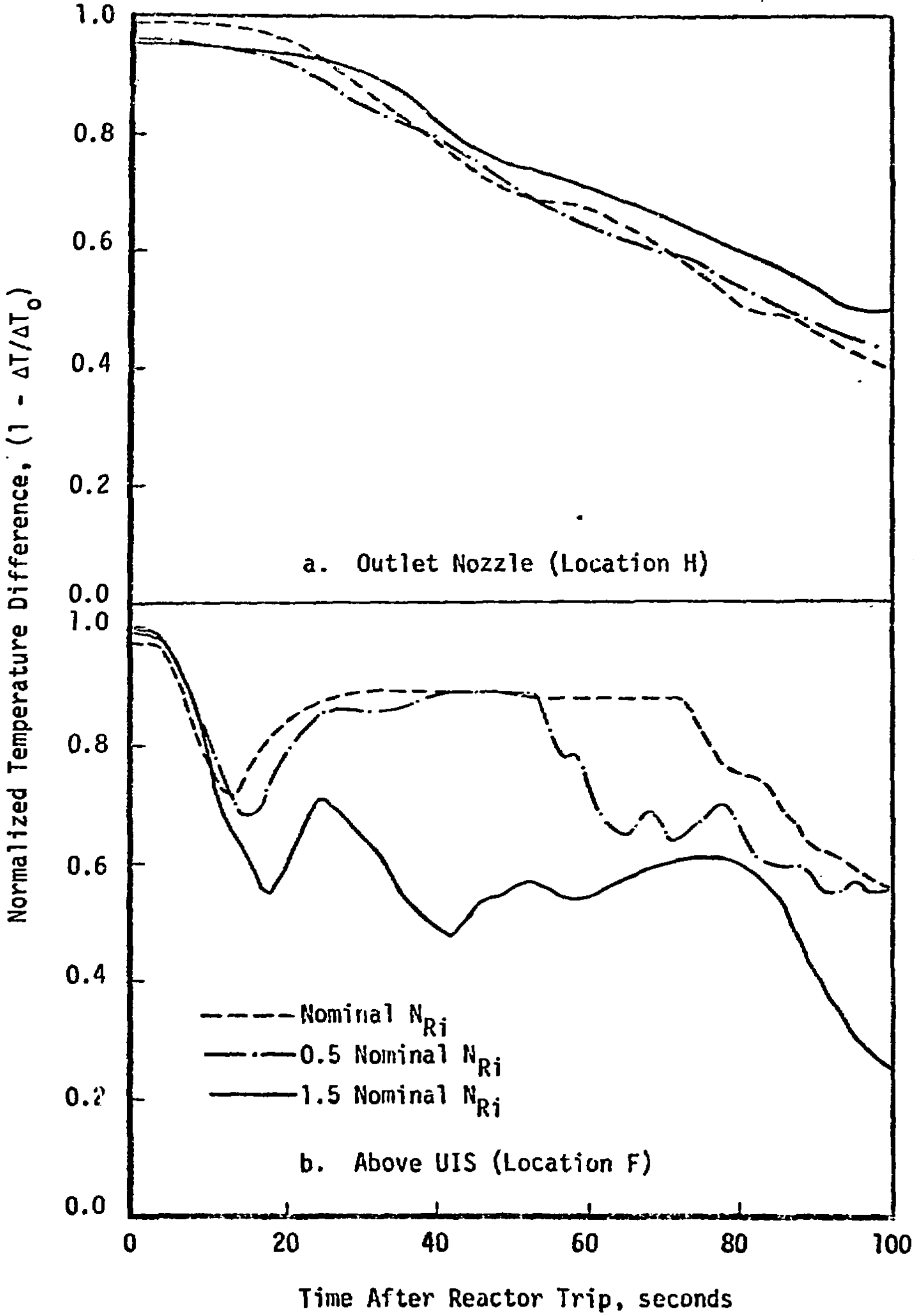

FIGURE 9. Effect of Richardson Number

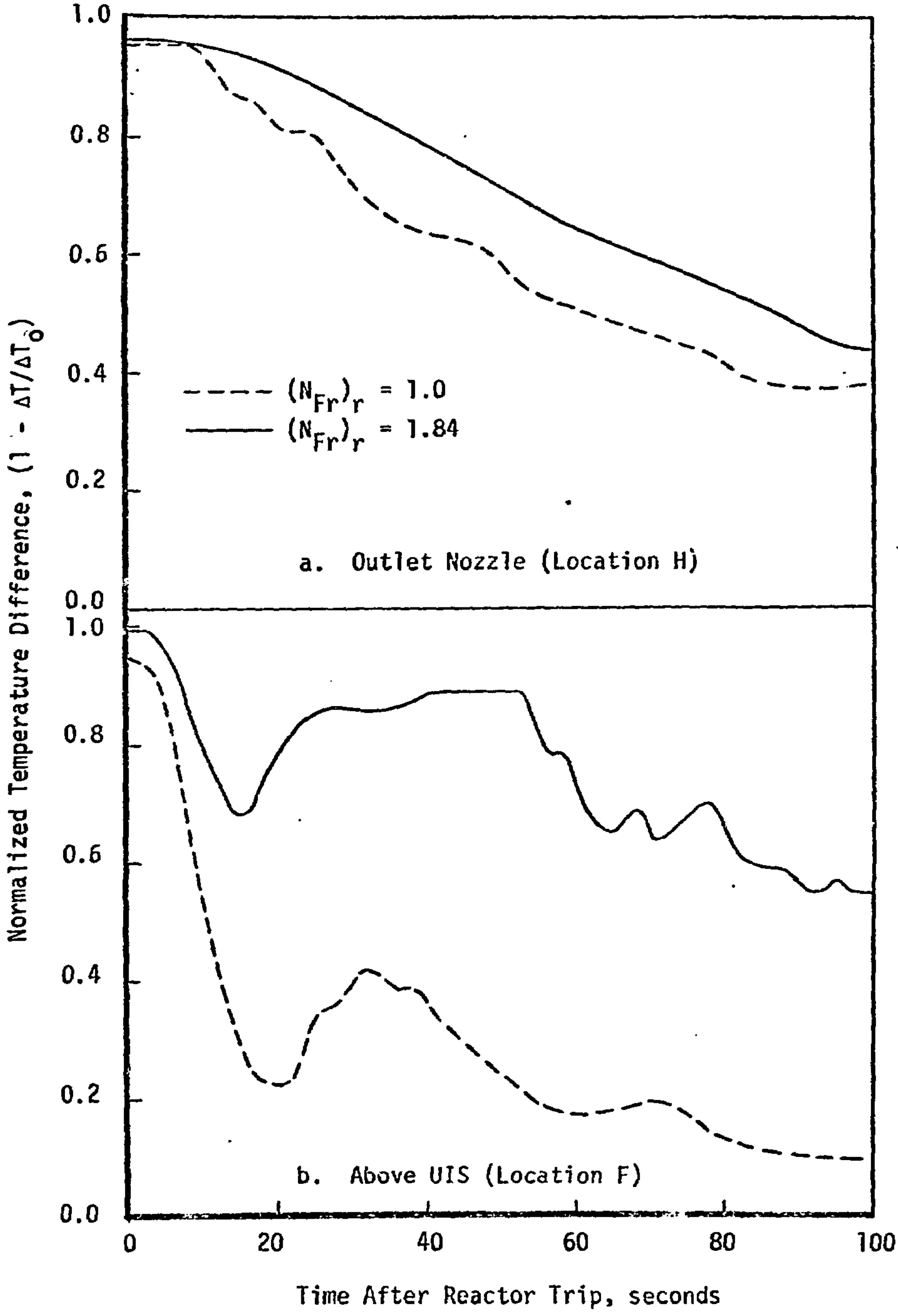

FIGURE 10. Effect of Froude Number