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ASSESSMENT OF SIMILARITY OF HFBR WITH SEPARATE EFFECTS TEST

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ABSTRACT

A Separate Effects Test (SET) facility was constructed in 1963 to demonstrate the feasibility of the HFBR design and to determine the core power limits for a safe flow reversal event. The objective of the task reported here is to review the capability of the test to scale the dominant phenomena in the HFBR during a flow reversal event and the applicability of the range of the power level obtained from the test to the HFBR.

The conclusion of this report was that the flow during the flow reversal event will not be similar in the two facilities. The causes of the dissimilarity are the differences in the core inlet friction, bypass path friction, the absence of the check valve in the test, and the materials used to represent the fuel plates. The impact of these differences is that the HFBR will undergo flow reversal sooner than the test and will have a higher flow rate in the final Natural Circulation Period. The shorter duration of the flow reversal event will allow less time for the plate to heat up and the larger flow in the Natural Circulation Period will lead to higher critical heat flux limits in the HFBR than in the test. Based on these observations, it was concluded that the HFBR can undergo flow reversal safely for heat fluxes up to 46,700 (BTU/hr ft²), the heat flux limit obtained from the 1963 test.

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1. EXECUTIVE SUMMARY

The Department of Energy (DOE) has recently been reviewing the safety and operational procedures of all of its research reactors. At Brookhaven National Laboratory (BNL), the High Flux Beam Reactor (HFBR) has been undergoing one of these reviews. While the extent of this inquiry is very encompassing, this report addresses only the applicability of a series of tests performed in 1963 to demonstrate the ability of the HFBR to successfully go through a flow reversal event. The purpose of these experiments were (and are) to establish a criterion of when a safe flow reversal could occur. This was accomplished by experimentally determining the power level (i.e., heat flux) after a scram that is low enough to allow the normally downward directed flow in the core to stop and to reverse (upward directed flow) under buoyancy driven conditions and without causing any fuel damage. More specifically, these experiments have been used to determine the heat flux limit (i.e., 46,700 BTU/hr ft²) and adiabatic heating rate (i.e., 99 F/s) below which the reactor fuel plate with peak power must remain at the time of flow reversal, in order to have a safe flow reversal during an unassisted main pump coast down with scram. Consequently, this report reviewed whether the 1963 test loop was properly scaled to capture the dominant characteristics of the hydrodynamic behavior of the HFBR during a flow reversal event and to determine if the conclusions drawn from the experiments are directly applicable to the HFBR.

The 1963 test was constructed to demonstrate the feasibility of the HFBR design and to determine the core power limits to allow this reactor to undergo a safe flow reversal event. A loop was constructed in 1963 of various pipe sizes to model the reactor vessel and the external piping of the HFBR system. A scaled heat exchanger and power supply were added to generate heat in a test section of either one or three prototypical channels. The four flow reversal valves in the HFBR were modeled by a ball valve and an orifice plate in the test.

The test did not include two current issues of concern. The first issue is that of the dissolved He that is in saturation in the actual reactor. The points of contention are the mechanism and the rate of dissolution of He during a flow reversal event and location of the gas accumulation. The second issue is that of the parallel channel effect which was also not addressed in the experiments since the single channel data was used to define the power limits. These two effects have not been discussed in this report since they were not part of the experiment and cannot be addressed in the context of a scaling analysis.

The experiments were carried out in two parts. The first part covered the actual flow reversal transient. This part represents the complete loss of power (AC and DC) to all the pumps (i.e., the main pumps, the pony motors, and shutdown system pumps). The reactor automatically scrams and the main pumps trip. The pump coast down will continue the downward flow through the core. This class of transient is categorized as a loss of power accident (LOPA). (However, it should be noted that the pony motor or the shutdown pumps in the HFBR would normally continue the forced down flow until the decay power was so low that a flow reversal event would be of no consequence.) Eventually in a LOPA, the flow decreases to a point that fluid will start voiding in the fuel channels, the steam will start to rise, and establish an upward directed

flow. Four flow reversal valves open in the HFBR in the first several seconds during the pump coast down and provide a return path between the plenums above and below the core. This will allow an adequate flow circulation path around the core where the flow rate is driven by the buoyancy force created by the voids in the fuel assemblies. The combination of how long it takes the flow to stop and to establish this upward flow, the decay power that it occurs at, the natural circulation flow rate it creates, the void distribution during the event, and what effect it has on the temperature of the fuel, are the crucial parameters this first part of the experiment was designed to characterize. This series of tests was performed at atmospheric pressure and by starting the experiments with down flow through the test core section at flow conditions similar to those just before the expected flow reversal event in the HFBR. The transient tests were performed at several different combinations of flow rates and power until the tests determined that the fuel plates would suffer damage at a heat flux of 48,000 (BTU/hr ft²) (Run 30) and would safely negotiate flow reversal if the heat flux was at or below 46,700 (BTU/hr ft²) (Run 28) with an adiabatic heating rate of less than 99 (F/s).

The second part of the experiment used the test to determine what power level could be sustained with buoyancy driven flow around the core. The power was increased in steps until a heat flux of 58,700 (BTU/hr ft²) (Run 48). A temperature excursion was observed at this heat flux. The differences in heat flux limits found in the two different test procedures for the same test section was attributed to the transient effects during the flow reversal process.

To accomplish the scaling review and calculate the necessary groups for comparison, the flow reversal event was divided into four phenomenologically distinct periods. These periods are the Coast Down Period, the Two Phase Downward Flow Period, the Two Phase Upflow Period, and the Stable Natural Circulation Period, respectively. The first two periods had downward flow through the core and the last two periods had two phase upward flow. Mass, momentum, and energy balances were formulated for each of these periods. The balance equations were non-dimensionalized and the dimensionless groups were then identified. Values of non-dimensional groups were computed for both facilities (i.e., the test loop and the HFBR). In cases where dissimilarity existed, the judgement of the vulnerability of the facilities to possible fuel damage was made by comparing the time constants for each period.

The conclusion of the scaling study is that the flow during the flow reversal event will not be similar in the two facilities. The causes of dissimilarity are the differences in the core inlet friction during normal downward flow, the bypass path friction (i.e., the flow reversal valves and reflector region), the absence of a check valve in the test loop, and the materials used to represent the fuel plate. However, the impact of these differences is that the HFBR will undergo a flow reversal sooner than the 1963 test and will have a higher critical heat flux in the stable natural circulation period than the 1963 test since higher flow rates are predicted in the HFBR. In general, it can be stated that the HFBR fuel plates would be less likely to sustain fuel damage than the 1963 test and the results generated by the test would be conservative for the HFBR application. Furthermore, this study supports a previous investigation (Appendix C) which concluded that the 1963 test facility did have fluid inertia behavior similar to the HFBR.

2. INTRODUCTION

The Department of Energy (DOE) has recently been reviewing the safety and operational procedures of all of its research reactors. At Brookhaven National Laboratory (BNL), the High Flux Beam Reactor (HFBR) (Figure 2.1) has been undergoing one of these reviews. While the extent of this inquiry is very encompassing, this report addresses only the applicability of a series of tests performed in 1963 (Figure 2.2) to demonstrate the ability of the HFBR to successfully go through a flow reversal event. The purpose of these experiments were (and are) to establish a criterion of when a safe flow reversal could occur. This was accomplished by experimentally determining the power level (i.e., heat flux) after a scram that is low enough to allow the normally downward directed flow in the core to stop and begin an upward directed flow under buoyancy driven conditions and not suffer any fuel damage. More specifically, these experiments have been used to determine the heat flux limit (i.e., 46,700 BTU/hr ft²) and adiabatic heating rate (i.e., 99 F/s) below which the peak reactor fuel plate must remain at the time of flow reversal, during an unassisted main pump coast down with scram, in order to have a safe flow reversal event. Consequently, this report reviewed whether the 1963 test loop was properly scaled to capture the dominant characteristics of the hydrodynamic behavior of the HFBR during a flow reversal event and to determine if the conclusions drawn from the experiments are directly applicable to the HFBR.

The 1963 test was constructed to demonstrate the feasibility of the HFBR design and experimentally determine the core power limits to allow this reactor to undergo a safe flow reversal event. A loop was constructed in 1963 of various pipe sizes to model the reactor vessel and the external piping of the HFBR system. A scaled heat exchanger and power supply were added to generate heat in a test section of either one or three prototypical channels. The four flow reversal valves in the HFBR were modeled by a ball valve and an orifice plate in the test.

The test did not include two current issues of concern today. The first issue is that of the dissolved He that is in saturation in the actual reactor. The points of contention are the mechanism and the rate of dissolution during a flow reversal event and location of the gas accumulation. The second issue is that of the parallel channel effect which was also not addressed in the experiments since the single channel data was used to define the power limits. These two effects have not been discussed in this report since they were not part of the experiment and cannot be addressed in the context of a scaling analysis.

The experiments were carried out in two parts. The first part covered the actual flow reversal transient. This part represents the complete loss of power (AC and DC) to all the pumps (i.e., the main pumps, the pony motors, and shutdown system pumps). The reactor automatically scrams and the main pumps trip. The pump coast down will continue the downward flow through the core. This class of transient is categorized as a loss of power accident (LOPA). (However, it should be noted that the pony motor or the shutdown pumps in the HFBR would normally continue the forced down flow until the decay power was so low that a flow reversal event would be of no consequence.) Eventually in a LOPA, the flow decreases to a point that fluid will start voiding in the fuel channels, the steam will start to rise, and establish an upward directed

FIGURE 2.1 HFBR Reactor Vessel

FIGURE 2.2 Schematic of the 1963 Test Facility

flow. Four flow reversal valves open in the HFBR in the first several seconds during the pump coast down and provide a return path between the plenums above and below the core. This will allow an adequate flow circulation path around the core where the flow rate is driven by the buoyancy force created by the voids in the fuel assemblies. The combination of how long it takes the flow to stop and to establish this upward flow, the decay power that it occurs at, the natural circulation flow rate it creates, the void distribution during the event, and what effect it has on the temperature of the fuel, are the crucial parameters this first part of the experiment was designed to characterize. This series of tests was performed at atmospheric pressure and by starting the experiments with down flow through the test core section at flow conditions similar to those just before the expected flow reversal event in the HFBR. The test transients were performed at several different flow and power combinations until the 1963 tests determined that the fuel plates would suffer damage at a heat flux of 48,000 (BTU/hr ft²) (Run 30) and could safely negotiate flow reversal if the heat flux was at or below 46,700 (BTU/hr ft²) (Run 28) with an adiabatic heating rate of less than 99 (F/s).

The second part of the experiment used the test to determine what power level could be sustained with buoyancy driven flow around the core. The power was continually increased until a heat flux of 58,700 (BTU/hr ft²) (Run 48) and temperature excursion was observed. The differences in heat flux limits found in the two different test procedures for the same test section was attributed to the transient effects during the flow reversal process.

3. OBJECTIVE

The objective is to assess the capability of the separate effects test to simulate thermal hydraulic conditions expected in the HFBR during a loss of power accident (LOPA). Specifically to assess the capability of the test to simulate flow reversal phenomena expected in the HFBR during a LOPA, and the applicability of the power levels obtained from the test to the HFBR. The likelihood of reaching a critical heat flux situation in the two facilities will also be assessed.

The flow reversal event is divided into phenomenologically distinct periods. The scalability of the test is assessed for each period by identifying the dimensionless groups from the non-dimensionalized balance equations for the mass, momentum and energy. The judgement on the similarity is made on the basis of comparing the non-dimensional groups representing the dominant phenomena. In cases where dissimilarity existed, the judgement of the vulnerability of the facilities to possible fuel damage was made by comparing the time constants for each period.

4. PHENOMENA DESCRIPTION

During the normal operation of the HFBR, the coolant flows down through the core region into the bottom reflector and up through the side reflectors into a hot leg. The hot leg exiting the vessel bifurcates and each section has its own pump, heat exchanger, and check valve. The two separate sections join again to return the cold coolant back into the upper part of the reactor vessel.

During LOPA, the pumps begin to coast down and the flow to the vessel and core decreases. A visualization of the event can be seen in Figure 4.1. At around 4900 gpm the pressure drop is about 3 psi across the transition plate and the flow reversal valves (which are situated near the core inlet to connect the core inlet to the top of the side reflector, see Figure 2.1) open. Part of the coolant flows through the core while the rest passes through valves to the side reflector. The sudden decrease in core flow occurs at time t_v as shown in Figure 4.1. The loop flow continues to decrease until the check valve at the pump discharge closes at time t_{cv} . The closing of the check valve isolates the vessel from the loop. The downward flow into the core continues but it is opposed by both the friction and buoyancy forces. The core flow ceases at time t_r . During the time period, t_{cv} to t_r , the fluid in the core will heat up. The stagnation condition will not last, as the fluid density in the core will decrease due to density changes and boiling, which will generate the upflow condition.

The reflector fluid is still subcooled and exerts hydrostatic force on the core fluid leading to an increase in buoyancy forces and upward flow in the core. Figure 4.1 also shows the schematic of density difference between the core and the reflector during the LOPA.

In the narrow region of time around the flow reversal point, the low sub-cooling fluid will enter the core from the reflector and boil. The two-phase mixture will leave at the top of the core, where some of the vapor phase will condense and the remaining vapor will flow up to the free surface. The exiting liquid phase will mix with the surrounding liquid in the upper reflector. The liquid phase at the top of the core and at the inlet of the bypass valve will eventually heat up and reach saturation conditions. The flow passes through the flow reversal valves and into the side reflector and eventually back to the bottom of the core. Larger friction drop across the flow reversal valves will oppose the flow reversal by increasing the pressure drop, while higher core power will facilitate flow reversal by its ability to generate higher void fractions.

The LOPA transient is divided into two distinct phases on the basis of flow direction. They are the normal flow phase and the reverse flow phase. The normal flow phase begins with the initiation of the accident and terminates when the flow in the core stops. This phase is further divided into two sub-periods; namely, Coast Down Period and Two-Phase Down Flow Period. As the flow through the core continues to coast down, the exit fluid temperature continues to increase. When this exit fluid temperature reaches saturation temperature, the fluid will start to boil. This event indicates the end of the Coast Down Period and the beginning of Two Phase Down Flow Period. During this period, bubbles will be generated and the voided region will increase. This will lead

FIGURE 4.1 General Behavior of Core Flow and Density During a LOPA

to an increase in buoyancy forces while the interfacial shear in two phase mixture will oppose the buoyancy forces and the downward flow. This phase ends when the core flow stagnates.

The second phase is the two phase upward directed flow period. This phase can also be divided into two subperiods; namely, Two Phase Upflow and Stable Natural Circulation. During the Two Phase Upward Flow Period, the liquid enters the core from the lower reflector region where the liquid temperature is hotter than at the core exit. The liquid boils in the core which leads to an increase in the buoyancy forces and accelerates the fluid upward. As the flow increases, the vapor generation begins to decrease and the flow acceleration slows down and eventually, the buoyancy forces and the friction forces balance leading to stable natural circulation period. The development of two phase upward flow is not smooth. As the vapor leaves the core there could be inflow of liquid at the top of the core. However, as the buoyancy force increases and the flow into the core at the bottom increases, the counter current flow at the top of the core will decrease and will eventually cease. The transient counter current flow at the top of the core during the flow reversal (near the stagnation condition) are beneficial since the fuel plates can be rewetted from the top.

4.1 Dissolved Helium Effect

The coolant in the HFBR is saturated with helium. During a LOPA, the system depressurizes due to the opening of the automatic depressurization valve, and the solubility of the He decreases. Some of the He will emerge from the coolant. The He emerging in the core during the down flow phase will either move up or be carried with the coolant into the reflector. The He will stay longer in the core where the coolant is flowing down than in the reflector region where the coolant is flowing up. The He in the core will decrease the mixture density and increase the buoyancy forces opposing the downward flow, thus assisting in flow reversal. Furthermore, if during this period the bypass valve is open, more of the loop flow will pass through these valves. Helium will also adversely affect the critical heat flux during low flow situations. However, if the system is depressurized either before the bypass valve opens or before the flow reversal event, most of the He would have come out of solution and migrated to the top of the vessel and not affect the flow reversal and subsequent stable natural circulation. The difficulty is in predicting the dissolved He concentration at the time of the flow reversal event.

The helium solubility can be estimated from the Henry's law for gases:

$$p = HX$$

where p is the partial pressure of helium in atmosphere, H is Henry constant and X is the solubility of the gas in the liquid and its unit are mole of gas per mole of solution. At normal operation, the system pressure is 220 psia and Henry's constant is 12×10^4 atm. Therefore, x is estimated as:

$$X_{\text{He}} = \frac{P}{H} = \frac{220 \text{ psia}}{(14.7 \text{ psia/atm})(12 \times 10^4 \text{ atm})} = 1.25 \times 10^{-4} \frac{\text{mole He}}{\text{mole mixture}}$$

The effect of He will depend upon the amount of He which can emerge from the solution. If all the He emerge at the same time then the void fraction in the two phase mixture in the HFBR near flow reversal time (1 atm, 150F) can be estimated from:

$$\alpha = \frac{X_{\text{He}} M_{\text{He}}}{M_{\text{D}_2\text{O}}} \frac{\rho_{\text{D}_2\text{O}}}{\rho_{\text{He}}} \approx \frac{1.25 \times 10^{-4} \times 4}{20} \left(\frac{1000 \text{ kg/m}^3}{0.15 \text{ kg/m}^3} \right) = 0.17$$

The void fraction due to helium will be significant if all of it came out at the same time. (This value greatly overestimates the possible added void fraction from He, however, this is noted here to supply an upper bound for the He void.) However, the loop flows will continue for about 60 seconds, which is plenty of time for the Helium to emerge from the fluid and escape the system since the cover gas would have depressurized by then (see Figure 4.2 [Cheng, 1989]). Also, there are many nucleation sights from fluid impurities and homogeneous nucleation due to the radiation effect. Thus, the solution can be assumed to be always saturated with He and in equilibrium. At the time of flow reversal, the system pressure is expected to be around 22 psia and the helium solubility will be 10% of the solubility at 220 psia. Therefore, if the coolant always remains saturated with He, then 90% of He would have emerged prior to flow reversal. (Recent RELAP5 calculations have substantiated that only 10% of the initial ~1 Kg of He in the system would be left by the time of the flow reversal [Slovik, 1990].) The calculation used the equilibrium dissolution model. The depressurization rate and He injection were adjusted to match plant blow down data. He would then contribute an additional void fraction of 0.017 and probably in the form of micro bubbles during flow reversal. Thus, He will have a negligible effect on the transient. However, the rate of He dissolution should be based on separate effects test. This report will not address the issue of He, but its effect is discussed for completeness.

4.2 Critical Heat Flux Considerations

During LOPA, the flow through the core changes from downflow to upflow and, eventually, to stable natural circulation. The core undergoes a low flow condition around the time of flow reversal where it is vulnerable to reaching the critical heat flux and the film boiling regime. This is because of the large void fraction at the flow stagnation point. Mishima et al. [1983] has shown that the critical heat flux for the HFBR type rectangular channels increases rapidly with the flow rate. Also they showed that critical heat flux for upflow was higher than in downflow for the same flow rate. The duration of vulnerability will depend upon core power, friction in the core, bypass valve, and fluid inertia.

4.3 Power Distribution Effect

The HFBR core consists of 532 flow channels with different powers. The phenomena described so far applies to all the channels. However, the timing

FIGURE 4.2 Depressurization Curve of the Cover Gas in the HFBR

will be different. The channels with larger power will have shorter duration between t_{cv} to t_r (see Figure 4.1). During this period, the buoyancy and friction are both opposing the downflow. In the core upflow period ($t > t_r$, Figure 4.1), however, the buoyancy forces will be opposing the friction forces. Voiding in the channel will increase both the forces. It is difficult to say which will increase faster. However, channels with different power levels will take different times to reach the stable natural circulation phase. Consequently, the power level in a channel will determine the flow rate and channel void fraction.

5. SEPARATE EFFECTS TEST FACILITY

A small scale separate effects test facility [Tichler, 1963], as shown in Figure 2.2, was set up to simulate the flows expected during a flow reversal event in the HFBR. The facility had full height fuel channels with electrically heated nickel plates representing fuel plates. Pipe sections were used to represent the core inlet section, core outlet, and side reflector. The heated channel in the test (0.098 in x 2 in x 22 in) was very similar to the channels (0.1 in x 2.46 in x 22.75 in) in the HFBR. The flow reversal bypass valves were modeled by a ball valve while the friction loss in the bypass valve was simulated by an orifice. The ratio of bypass path area to core area varied from 0.22 to 0.75 in the test. The ratio in the HFBR is 0.36. A pump and heat exchanger representing the external loop in the HFBR was also provided in the test facility.

Two types of tests were performed in this facility. The first type of tests assessed the transient flow reversal phenomena in the HFBR. These tests were performed with two configurations, namely, single channel and three similar channels. The velocity in the channels varied from 1 ft/sec to 9 ft/sec and the heat flux varied from 9000 BTU/hr ft² to 51,000 BTU/hr ft². The velocities covered the HFBR loop flow rates from 400 gpm to 3600 gpm. Hence, all tests were begun below the flow rate of 4900 gpm where the flow reversal valves open in the HFBR. The heat flux range in the test covers the range expected in the HFBR. The HFBR power near the time of check valve closing is 2000 KW (60 seconds after scram for 60 MW operation), which is equivalent to the average core heat flux of 19000 BTU/hr ft².

The tests were begun with the pump running and the bypass valve open until the system achieved a steady state condition. The transient was initiated by tripping the pump. No check valve was present in the test facility. It was observed that there was voiding and flow reversal in all the runs with heat flux exceeding 12,000 BTU/hr ft². There were no flow measurements and the conclusions about flow reversal were made on the basis of visual observation of voiding, pressure, and temperature. The plate temperature at the top of the core was close to the boiling point (240°F) after the flow reversal event which also indicated the event in progress. Brief periods of rapid temperature increase of 7 to 15°F/sec were observed, but the total temperature increase was on the order of 100°F. Only two tests with the single channel test section (29 and 30) showed burnout and a rapid temperature rise of 40°F/sec. Test 28 had a single channel and was the highest heat flux test for which no burnout was observed. The heat flux was 46,700 BTU/hr ft². This heat flux became the basis of core power and safety procedure in the HFBR.

The second set of tests were performed to assess the stable natural circulation phase after the flow reversal event was established. These tests were performed for low and high subcoolings for the fluid in the reflector. The test report states that a stable natural circulation was established for several different conditions and no damage to the plate was observed. The heat flux varied from 10,400 BTU/hr ft² to 59,400 BTU/hr ft² depending on inlet conditions.

There are four significant differences between the test and the HFBR. First, the test does not account for dissolved Helium as required in the HFBR. It is unclear whether this is an important issue since the flow reversal event occurs 60 seconds after the depressurization begins and most of the He is expected to have left the fluid at the flow reversal point. (An analysis using an equilibrium release model for the helium dissolution indicated only about 10% of the original 1 kg of He would still be in the system at the time of flow reversal, see Section 4.1.) This effect will not be considered in this report. The second difference is that check valves in the loops close at low flow situations in the HFBR while the pump in the test coast down and stop. No loop isolation valve was used for the tests of interest. The argument provided for this difference is that the test pump has no flywheel and therefore will coast down rapidly which would make the results more conservative. This difference will be addressed in this report. The third difference is in the axial power distribution in the channels. In the HFBR, there is peaking in the middle of the channel while the test was performed with uniform power distribution. The hydraulic behavior, especially the natural circulation conditions, are only dependent on the total power in a channel, so it will not be affected by this. However, there will be a difference in the local burnout conditions, though the effect on fuel temperature will be reduced due to high thermal conductivity of the aluminum (0.21 kW/mK) in comparison to nickel thermal conductivity (0.08 kW/mK). Finally, the HFBR has parallel channels with different powers. The flow through any channel will be affected by other channels due to the dependency of the imposed pressure drop on the net core flow. The runs of interest in the test have only single heated channel and therefore, do not have parallel channel effects in their results.

6. ANALYSIS

As explained in Section 4, the LOPA can be divided into two distinct phases based on direction of the flow in the core. These two phases are further divided into subperiods based on the thermal hydraulic conditions. In this section, similarity groups will be developed for each of the subperiods. The dominant groups will be identified which will then be used to assess the similarity between the two facilities.

6.1 Normal Flow Phase

During this period of the LOPA, the flow is always downward in the core. This period is subdivided into two subperiods, namely, the Coast Down Period and the Two Phase Downward Flow Period. The coast down period begins with the loss of power to the pump and ends when the liquid becomes saturated at the bottom of the core. The second subperiod begins at this time and ends when the net flow through the core stops.

6.1.1 Coast Down Period

During this period, the pump is coasting down and decreasing the loop flow. This occurs in both the HFBR and test loop. As the net loop flow in the HFBR decreases below 800 gpm, the loop check valves close and the vessel is isolated from the loop. However, the loop flow in the test continues to decrease to stagnation since the test loop doesn't have a check valve. The flow through the core begins to decrease rapidly as the fluid inertia in the core decreases due to friction and buoyancy forces. The flow in the core stops after the loop flow has stopped. The flow will decrease due to friction in the loop and in the vessel (core and bypass path).

6.1.1.1 Formulation

It is assumed that the liquid density is constant and so the mass and momentum balances are decoupled from the energy balance. The loop consists of pipes, pump and heat exchanger. Figure 6.1 shows a schematic of the flow paths for the test and HFBR. The balance equations consists of mass balance and momentum balance. The loop consists of pipes of different sizes and bends, which can be grouped into four segments. The mass balance for each segment is:

$$\rho_L U_L A_L = \rho_L U_{Li} A_{Li}, i = 1, 4 \quad (6-1)$$

The momentum balance is integrated over the whole loop and is:

$$\rho_L A_L I_L \frac{dU_L}{dt} = - (P_5 - P_4) + (E_4 - E_5) \rho_L g - F_L \frac{1}{2} \rho_L U_L^2 + \Delta P_p \quad (6-2)$$

Schematic of Flow Path

FIGURE 6.1 Schematic of Facilities

bnl
aui

$$I_L = \sum_{i=1}^4 L_{Li} / A_{Li} \quad (6-3)$$

$$F_L = \sum_{i=1}^4 \frac{f_{Li} L_{Li}}{D_{Li}} \left(\frac{A_L}{A_{Li}} \right)^2 + \sum_{i=1}^4 K_{ELBi} \left(\frac{A_L}{A_{ELBi}} \right)^2 + \sum_{i=1}^4 K_{vi} \left(\frac{A_L}{A_{vi}} \right)^2 \quad (6-4)$$

where I_L and F_L are the net inertia and friction factor in the loop. Furthermore, U_L and A_L are representative loop velocity and area while U_{Li} and A_{Li} are the velocity and area of the different pipe sections of the loop. E_4 and E_5 are the end point elevations of the loop, K_{ELBi} and K_{vi} are the loss coefficients for the elbows and the valves. ΔP_p is the pump head which depends upon loop flow and pump speed.

Similarly, integrated mass and momentum balance [Ishii & Kataska, 1983] are written for the core, reflector and the bypass flow paths.

$$\rho_\ell A_L U_L = \rho_\ell A_C U_C + \rho_\ell A_B U_B \quad (6-5)$$

$$\rho_\ell A_C U_C = \rho_\ell A_R U_R \quad (6-6)$$

$$P_5 = P_6 - (E_5 - E_6) \rho_\ell g \quad (6-7)$$

$$\rho_\ell I_B A_B \frac{dU_B}{dt} = -(P_4 - P_6) - F_B \frac{1}{2} \rho_\ell U_B^2 + \rho_\ell g (E_6 - E_4) \quad (6-8)$$

$$I_B = \frac{L_B}{A_B} \quad (6-9)$$

$$F_B = K_B + f_B L_B / D_B$$

where A_B , A_C , and A_R are the areas and U_B , U_C and U_R are the velocities in the bypass path, core, and the reflector region, respectively. In addition L_B and f_B are the length and the friction factors in the bypass path.

$$E_6 - E_4 = L_{CE} + L_C - L_{RV} \quad (6-10)$$

where L_{CE} , L_C and L_{RV} are the unheated core entrance and core channel lengths and the reflector height, respectively.

$$\rho_l I_C A_C \frac{dU_C}{dt} = (P_6 - P_2) + (E_6 - E_2) \rho_l g - F_C \frac{1}{2} \rho_l U_C^2 \quad (6-11)$$

$$I_C = \frac{L_{CE}}{A_{CE}} + \frac{L_C}{A_C} \quad (6-12)$$

$$F_C = \frac{f_C L_C}{D_C} + \frac{f L_{CE}}{D_{CE}} \left(\frac{A_C}{A_{CE}} \right)^2 + K_{Ci} + K_{Ce} \quad (6-13)$$

where L_C , D_C , L_{CE} , and D_{CE} are the lengths and the hydraulic diameters of the heated core channels and unheated core entrance section. K_{Ci} and K_{Ce} are the loss coefficients for the core inlet and exit sections. The reflector region is very complicated and has been approximated with a constant area channel [Tichler, 1988].

$$\rho_l I_R A_R \frac{dU_R}{dt} = (P_2 - P_4) - (E_4 - E_2) \rho_l g - F_R \frac{1}{2} \rho_l U_R^2 \quad (6-14)$$

$$I_R = \frac{L_R}{A_R} \quad (6-15)$$

$$F_R = \frac{f_R L_R}{D_R} \quad (6-16)$$

These equations (6-1 through 6-16) are combined to eliminate pressure and gravity terms.

$$\begin{aligned} \rho_l A_L I_L \frac{dU_L}{dt} + \rho_l A_B I_B \frac{dU_B}{dt} = & - F_L \frac{1}{2} \rho_l U_L^2 + \Delta P_P \\ & - F_B \frac{1}{2} \rho_l U_B^2 \end{aligned} \quad (6-17)$$

$$\begin{aligned} \rho_l A_L I_L \frac{dU_L}{dt} + \rho_l A_C (I_C + I_R) \frac{dU_C}{dt} = & - F_L \frac{1}{2} \rho_l U_L^2 + \Delta P_P \\ & - (F_C + F_R) \left(\frac{A_C}{A_R} \right)^2 \frac{1}{2} \rho_l U_C^2 \end{aligned} \quad (6-18)$$

From Equation 6-5, we get:

$$\rho_L A_L \frac{dU_L}{dt} = \rho_L A_B \frac{dU_B}{dt} + \rho_L A_C \frac{dU_C}{dt} \quad (6-19)$$

Equations 6-17 through 6-19 are further combined to eliminate terms for loop and bypass path momentum terms.

$$A_C \rho_L \frac{dU_C}{dt} \{ (I_C + I_R) (I_L + I_B) + I_L I_B \} = B_L I_B + B_C (I_L + I_B) - B_B I_L \quad (6-20)$$

where

$$B_L = - F_L \frac{1}{2} \rho_L U_L^2 + \Delta P_p \quad (6-21)$$

$$B_C = - (F_C + F_R) \left(\frac{A_C}{A_R} \right)^2 \frac{1}{2} \rho_L U_C^2 \quad (6-22)$$

$$B_B = - F_B \frac{1}{2} \rho_L U_B^2 \quad (6-23)$$

$$I_T = (I_C + I_R) (I_L + I_B) + I_L I_B \quad (6-24)$$

The reference velocities will be different for the core, bypass path and the loop and will be related through the steady state conditions. The area and the length of the core are used as reference quantities. Using the approach described in Appendix A, and Equation 6-5, we get expressions for reference velocities:

$$\frac{U_{Cr}}{U_{Br}} = \sqrt{ (F_C + F_R \left(\frac{A_C}{A_R} \right)^2) / (F_B) } \quad (6-25)$$

$$U_{Cr} = (U_{Cr} A_C + U_{Br} A_B) / A_B \quad (6-26)$$

$$U_{Lr} = U_{Cr} (A_C + A_B) \sqrt{ (F_C + F_R \left(\frac{A_C}{A} \right)^2) / (F_B) } / A_L \quad (6-27)$$

$$\begin{aligned}
\frac{d\bar{U}_C}{dt} = & - \frac{F_L \tau_r U_{Cr}^2}{U_{Cr} A_r} \frac{I_B}{I_T} \frac{1}{2} \bar{U}_L^2 + \frac{\Delta P_r \tau_r}{A_r U_{Cr}} \frac{I_B}{I_T} \Delta \bar{P} \\
& - (F_C + F_R \left(\frac{A_C}{A_R}\right)^2) \frac{(I_L + I_B)}{I_L} \frac{U_{Cr}}{A_r} \tau_r \frac{1}{2} \bar{U}_C^2 \\
& - F_B \frac{I_L}{I_T} \left(\frac{U_{Br}^2 \tau_r}{U_{Cr} A_r} \right) \frac{\bar{U}_B^2}{2}] \quad (6-28)
\end{aligned}$$

Where $\bar{U}_C$, $\bar{U}_B$ and $\bar{U}_L$ are the non-dimensional velocities in the core, bypass path and the loop, t is the non-dimensional time, and τ_r is the time constant of the momentum equation.

The single phase loop flow is governed by frictional forces and pump head. There are four groups which represent these forces:

$$G_{1,1} = \frac{F_L \tau_r U_{Cr}^2 I_B}{2 U_{Cr} A_r I_T}$$

$$G_{1,2} = \frac{\Delta P_r \tau_r I_B}{A_r U_{Cr} I_T}$$

(6-29)

$$G_{1,3} = \frac{(F_C + F_R \left(\frac{A_C}{A_R}\right)^2) (I_L + I_B) U_{Cr} \tau_r}{2 I_T A_r}$$

$$G_{1,4} = \frac{F_B U_{Br}^2 \tau_r I_L}{2 U_{Cr} A_r I_T}$$

The time constant for the test will be the time which makes the right hand side of Equation (6-28), of the order of one as the left side is of the order of 1.

$$\tau_{r,\text{test}} = 1 / |G_{1,2} - G_{1,1} - G_{1,3} - G_{1,4}| \quad (6-30)$$

In the case of the HFBR, the loop check valve closes and the loop is disconnected from the vessel. The flow through the reverse flow valve will change direction. It is assumed that the time constant for flow reversal through this valve is very small. The flow configuration during this phase consists of downflow through the core, upflow through the reflector and return flow through the reverse flow valve to the top of the core. The balance equations and the characteristic velocities for the HFBR will be different from the test.

$$U_{Br} = U_{Cr} A_C / A_B \quad (6-31)$$

$$U_B = U_C A_C / A_B \quad (6-32)$$

$$\frac{d\bar{U}_C}{dt} = - \left[(F_C + F_R \left(\frac{A_C}{A_R}\right)^2) \frac{\tau_r U_{Cr}}{(I_B + I_C + I_R) A_r} + F_B \left(\frac{A_C}{A_B}\right)^2 \frac{\tau_r U_{Cr}}{(I_B + I_C + I_R)} \frac{1}{A_r} \right] \bar{U}_C^2 \quad (6-33)$$

Therefore, τ_r is estimated from 6-33 for the HFBR.

$$\tau_{r, HFBR} = 2 / \left[(F_C + F_R \left(\frac{A_C}{A_R}\right)^2 + F_B \left(\frac{A_C}{A_B}\right)^2) \frac{U_{Cr}}{A_r (I_B + I_C + I_R)} \right] \quad (6-34)$$

The time to reach the end of the Coast Down Phase can be estimated from Equation 6-33:

$$\bar{U}_C = \frac{1}{1 + \bar{t}} \quad (6-35)$$

6.1.1.2 Assessment of Similarity

The flow in the test will coast down and the comparison will be made from the time at which the fluid velocity in the test section corresponds to the fluid velocity in the core of the HFBR at the time of check valve closing (800 gpm loop flow). The transient prior to these conditions is not important for core safety as the flow is high and there will be forced flow cooling.

The reference core velocity in the HFBR at the time of the loop check valve closing is estimated from Equations 6-25 through 6-27. These equations will require an estimate of friction factor.

$$f_{lam} = \frac{16}{Re} \quad Re \leq 2500 \quad (6-36)$$

$$f_{tr} = \frac{0.046}{Re^{0.2}} \quad Re \geq 5000 \quad (6-37)$$

$$f = f_{lam} + (f_{tr} - f_{lam}) (Re - 2500) / 2500 \quad (6-38)$$

However, the process of estimating the flow will be iterative as f depends on the flow rate. Table 6.2 summarizes the geometric parameters and properties of the material which will be needed for the evaluation of the non-dimensional groups (Eq. 6-29).

If all the flow went through the core, the core velocity will be:

$$U_C = \frac{0.0504 \text{ m}^3/\text{s}}{0.0836 \text{ m}^2} = 0.6 \text{ m/s} \quad (6-39)$$

and the corresponding Reynolds number is:

$$Re = \frac{0.6 \text{ m/s} \times 1000 \text{ kg/m}^3 \times 0.0048 \text{ m}}{547 \times 10^{-6} \text{ kg/ms}} = 5300 \quad (6-40)$$

The coast down period ends when the fluid at the core exit is saturated. We will consider the channel in the HFBR which has average heat flux of 46,700 BTU/ft² hr and the fluid velocity to achieve saturation conditions at the exit of this channel is:

$$U_C = \frac{q'' L_C}{\rho_L C_p (T_{sat} - T_L)} \frac{4}{D_C}$$

$$= \frac{147.3 \text{ kJ/m}^2\text{s} \times 0.58 \text{ m} \times 4}{1000 \text{ kg/m}^3 \times 4.2 \text{ kJ/kg K} \times 55 \text{ K} \times 0.0048 \text{ m}} = 0.31 \text{ m/s} \quad (6-41)$$

and corresponding Reynolds number is:

$$Re = 2738 \quad (6-42)$$

Therefore, the flow will be in transition flow regime and f is estimated from Equation 6-38.

Using Equations 6-9, 6-13, 6-26, and 6-27 we estimate U_{Cr} for loop flow of 800 gpm (0.05 m³/s) in the HFBR.

TABLE 6.1 LOOP DIMENSION FOR TEST FACILITY

<u>Pipe</u>				
<u>Length</u>	<u>Diameter</u> <u>m</u>	<u>A</u> <u>m²</u>	<u>L/D</u>	<u>L/A</u> <u>m⁻¹</u>
0.51	0.0381	0.00114	13.3	447.3
3.53	0.0254	0.00051	138.9	6966
0.87	0.019	0.00028	45.8	3068
1.47	0.0127	0.000127	115.7	11604

<u>Valves</u>		
<u>Type</u>	<u>Diameter</u> <u>m</u>	<u>Loss Coefficient</u> <u>Equivalent (L/D)</u>
Gate Valve	0.0381	13
Gate Valve	0.0254	13
Diaphram	0.019	13
Gate Valve	0.0127	13

Elevation with respect to bottom of reflector

<u>Location</u>	<u>Elevation</u>
Exit to vessel	16 ft (4.88 m)
Inlet at reflector	5.96 ft (1.82 m)

<u>Elbows (Standard)</u>			
<u>Number</u>	<u>Diameter</u> <u>m</u>	<u>Loss Coefficient</u> <u>Equivalent (L/D)</u>	<u>Total Loss</u> <u>Equivalent L/D</u>
1	0.0381	30	30
4	0.0254	30	120
3	0.019	30	90
4	0.027	30	120

TABLE 6.2 GEOMETRY, PROPERTIES AND FLOW CONDITIONS

<u>ITEMS</u>	<u>UNIT</u>	<u>HFBR</u>	<u>SET (1 CHANNEL)</u>	<u>COMMENTS</u>
Fluid		D ₂ O	H ₂ O	
L _{CE}	m	0.330	0.356	See Appendix C
A _{CE}	m ²	0.1125	0.00135	See Appendix C
D _{CE}	m	0.378	0.041	
L _C	m	0.5776	0.559	L _R , Appendix C
A _C	m ²	0.0836	1.26 x 10 ⁻⁴	A _R , Appendix C
D _C	m	0.0048	0.0047	
L _{Rh}	m	0.464	0.69	
L _{Rv}	m	0.908	0.69	
L _r	m	1.372	1.38	
A _R	m ²	2.94	4.56 x 10 ⁻³	
D _R		1.93	0.076	
L _B	m	0.0163	0.87	See Appendix A Note (0.15m with area 4.6x10 ⁻³ m ²)
A _B	m ²	0.03	0.002	See Appendix A
D _B	m	0.028	0.051	
$\bar{A}_{B,min}$	m ²	0.03	2.63 x 10 ⁻⁵	See Appendix A

TABLE 6.2 (CONTINUED)

<u>ITEMS</u>	<u>UNIT</u>	<u>HFBR</u>	<u>SET (1 CHANNEL)</u>	<u>COMMENTS</u>
K_{Ci}		0.2	0.46	Normal Flow, contraction
K_{Ce}		1.0	1.0	Normal Flow, expansion
K_{Ci}		1.0	1.0	Reverse Flow, expansion
K_{Ce}		0.49	0.49	Reverse Flow, contraction
K_R		0.0	0.0	
K_B		4.33	2.85*	See Appendix A
A_f	m^2	33.3	0.053	Heated Area
δ_f	m	1.27×10^{-3}	6.35×10^{-4}	Fuel Plate Thick- ness
q	kW	2000		
q"	kW/m^2 s	60.6	147.3	Average Heat Flux
k_c	kW/mK	605×10^{-6}	664×10^{-6}	Coolant, Thermal Conductivity
$C_{p,c}$	kJ/kg K	4.22	4.18	Coolant, Specific Heat

TABLE 6.2 (CONTINUED)

<u>ITEMS</u>	<u>UNIT</u>	<u>HFBR</u>	<u>SET</u> <u>(1 CHANNEL)</u>	<u>COMMENTS</u>
ρ_f	kg/m ³	3511	8896	Fuel Density
k_f	kW/mK	0.21	0.083	Fuel, Specific Heat
$C_{p,f}$	kJ/kg K	0.85	0.43	Fuel, Specific Heat
P_1	bar	1.5	1.5	
T_1	K	323	323	
U_c	m/s	0.6	0.755	
μ_C	kg/ms	0.00028	0.00028	Liquid Viscosity
μ_g	kg/ms	0.000012	0.000012	Vapor Viscosity
ρ_l	kg/m ³	1095	988	
ρ_g	kg/m ³	0.95	0.86	
β	1/K	4.3×10^{-4}	4.6×10^{-4}	
σ	N/m	0.068	0.068	Surface Tension

*Based on Minimum Area Velocity

$$U_{Cr} = 0.48 \text{ m/s} \quad (6-43)$$

The time scale for the HFBR is estimated from Equation 6-34:

$$I_B = 0.54 \text{ m}^{-1}$$

$$I_C = 9.85 \text{ m}^{-1}$$

$$I_R = 0.47 \text{ m}^{-1}$$

$$\tau_{R, HFBR} = 0.106 \text{ s} \quad (6-44)$$

Time to the end of the coast down period is estimated from Equation 6-35 and 6-41:

$$t = \tau_{r, HFBR} \left(\frac{U_{cr}}{U_C} - 1 \right)$$

$$t = 0.058 \text{ seconds} \quad (6-45)$$

Therefore, the voiding in the channel considered here ($q''=46,700 \text{ BTU/ft}^2 \text{ hr}$) will occur soon after the check valve is closed. For average HFBR channel:

$$q'' = \frac{\text{Decay Power}}{\text{Total Fuel Area}} = \frac{2000 \text{ kW}}{33 \text{ m}^2} = 60.6 \frac{\text{kW}}{\text{m}^2} \quad (6-46)$$

and

$$t = 0.29 \text{ seconds} \quad (6-47)$$

The time scale for the test facility will be evaluated now from Equations 6-9, 6-10, 6-13, 6-15, and 6-28. The dimensions are listed in Tables 6.1 and 6.2.

$$I_L = 22085 \text{ m}^{-1}$$

$$I_R = 302.6 \text{ m}^{-1}$$

$$I_C = 4700 \text{ m}^{-1}$$

$$I_B = 82 \text{ m}^{-1}$$

$$I_T = 1.11 \times 10^8 \text{ m}^{-2}$$

The four groups identified in Equation 6-28 have been computed. As no information about pump head was available, it is assumed that the pump does not provide any head. However, we are interested in comparing the time constant for the two facilities. If the time constant for the test without the pump head is greater than in the HFBR, then the time constant for the test with the pump will be even higher than in the HFBR. The four groups are:

$$G_{1,1} = 0.4 \times 10^{-3} \tau_r$$

$$G_{1,2} = 0.0$$

(6-48)

$$G_{1,3} = 0.88 \tau_r$$

$$G_{1,4} = 0.88 \tau_r$$

Thus, the dominant groups are the two friction groups in the vessel ($G_{1,3}$ and $G_{1,4}$) and they will govern the time scale. The time constant is estimated using Equation 6-30.

$$\tau_{r,\text{test}} = 0.57 \text{ seconds}$$

(6-49)

The reference velocities in the core and the bypass path used in the estimate of time constant are:

$$U_{Cr} = 0.48 \text{ m/s}$$

$$U_{Br} = 0.0058 \text{ m/s}$$

Comparison of time scales for the HFBR (Equation 6-44) and for the test (Equation 6-49) indicates that the core flow will slow down faster in the HFBR and will reach the end of the coast down period sooner than in the test. Actual time for the test can be estimated from Equations 6-28 and 6-41 by neglecting smaller terms and assuming that the velocity ratio between the bypass path and the core is maintained.

$$\frac{d\bar{U}_C}{dt} = -U_C^2$$

$$\bar{U}_C = \frac{1}{t + 1} \quad (6-50)$$

$$t = \tau_{r, \text{test}} \left(\frac{U_{Cr}}{U_C} - 1 \right) = 0.3 \text{ seconds} \quad (6-51)$$

Therefore, it is concluded that the test will take longer time to reach the end of the coastdown period than the HFBR. It should be noted that a previous study (Appendix C) to investigate the fluid inertia effects in the 1963 test facility and the HFBR found them to be similar. This analysis supports that claim since the ratios I_B/I_C and I_R/I_C are very similar for the two facilities.

6.1.2 Two Phase Downward Flow Period

This period begins when the coolant at the bottom of the core becomes saturated and leads to vapor generation. The initial vapor will be in the form of bubbles. Depending on the coolant velocity, these bubbles will have three possibilities: they can be carried with the coolant, they can stagnate, or they can move up. Initially, the bubbles will be carried with the coolant, and as the coolant velocity decreases, the slip between the bubbles and the liquid increases. When the coolant flow reaches a critical flow rate, the bubbles will stagnate. However, the coolant will continue to slow down due to friction and buoyancy forces, and when the coolant flow is lower than the critical flow, the bubbles will move up. There will be two effects of the upward movement of the bubbles; first, the voided region will increase; second, the bubbles will condense when they come in contact with the subcooled liquid and thus, will decrease the subcooling. The large fraction of energy transferred to the fluid will stay in the fluid. As the warmer coolant flows down, it will generate more vapor and therefore, increase buoyancy and frictional forces. The coolant will rapidly slow down and stagnate. The time constant for this period will be smaller than the previous period as buoyancy will also be opposing the flow. This event will mark the end of the Normal Flow Phase.

6.1.2.1 Formulation

The phenomena dominating this period are confined to the core. The flows are small, so the relative velocity effect will be important. The effect of bypass flow and the flow in the reflector region can be neglected as the gravity effect will be the dominating effect. So the pressure drop across the core

(heated section) will be assumed to be constant and equal to the hydrostatic pressure drop imposed by the liquid in the bypass path (6 to 4) and the vertical section of the reflector region (3 to 4) as shown in Figure 6.1.

$$P_2 - P_1 = (E_1 - E_2) \rho_l g = L_C \rho_l g \quad (6-52)$$

A drift flux formulation is used for the flow in the core. It is further assumed that the fluid is always in equilibrium. The local balance equations are as follows [Ishii & Kataoka, 1983]:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial}{\partial z} (\rho_m U_m) = 0 \quad (6-53)$$

$$\begin{aligned} \frac{\partial (\rho_m U_m)}{\partial t} + \frac{\partial}{\partial z} (\rho_m U_m^2) = & - \frac{\partial P}{\partial z} - \rho_m g - \frac{\partial}{\partial z} \left[\frac{\alpha \rho_l \rho g}{(1-\alpha) \rho_m} v_{gj}^2 \right] \\ & - \left[\frac{f}{2D} + \frac{1}{2} K \delta (z - z_i) \right] \rho_m U_m |U_m| \end{aligned} \quad (6-54)$$

$$\frac{\partial (\rho_m H_m)}{\partial t} + \frac{\partial}{\partial z} (\rho_m U_m H_m) = \frac{h(T_s - T)\epsilon}{A_C} - \frac{\partial}{\partial z} \left(\frac{\alpha \rho_g \rho_l}{\rho_m} H_{fg} v_{gj} \right) \quad (6-55)$$

The energy balance for the solid is given by the following equation:

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} + k_s \nabla^2 T_s = \dot{q} \quad (6-56)$$

where T_s is the temperature in the solid. The boundary condition between the solid and the liquid is given as:

$$-k_s \frac{\partial T_s}{\partial y} = h (T_s - T) \quad (6-57)$$

The temperature in the solid is assumed to be uniform as the solid plate thickness (δ_s) and the Biot number are small.

$$BIOT = \frac{h \delta_s}{k_s} \quad (6-58)$$

The Biot number is estimated for laminar flow and it is:

$$\text{BIOT} = 0.0126 \quad (6-59)$$

Therefore, the temperature variation across the plate thickness is neglected. Furthermore, as the plate is 10 times longer than it is wide, the temperature variation across the plate is also neglected.

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} + K_s \frac{\partial^2 T_s}{\partial z^2} = \dot{q} - \frac{h (T_s - T)}{\delta_s} \quad (6-60)$$

The constitutive relationships and definition of variables are as given here. The drift velocity description is from Ishii [1977]:

$$V_{gj} = (C_o - 1)j + \langle\langle V_{gj} \rangle\rangle$$

The profile functions C_{ob} and C_{oa} , for bubbly flow and annular flow are as follows:

$$C_{ob} = 1.35 - 0.35 \sqrt{\rho_g / \rho_l} \quad (6-61)$$

$$C_{oa} = 1 + (1 - \alpha_1) / (\alpha_1 + 4 \sqrt{\rho_g / \rho_l})$$

$$\begin{aligned} C_o &= C_{ob} & C_{ob} &\leq C_{oa} \\ &= C_{oa} & C_{ob} &> C_{oa} \end{aligned}$$

$$\langle\langle V_{gjb} \rangle\rangle = 1.4 (\sigma g / \rho_l)^{0.25}$$

$$\langle\langle V_{gja} \rangle\rangle = \frac{(1 - \alpha_2)(g D_c (1 - \alpha_2) / 0.015)^{0.5}}{(\alpha_2 + 4 \sqrt{\rho_g / \rho_l})}$$

$$\langle\langle V_{gj} \rangle\rangle = \langle\langle V_{gjb} \rangle\rangle, \quad C_{ob} \leq C_{oa}$$

$$= \langle \langle V_{gja} \rangle \rangle, \quad C_{ob} > C_{oa}$$

$$\rho_m = \alpha \rho_g + (1-\alpha) \rho_l \quad (6-62)$$

$$H_m = c H_g + (1-c) H_f \quad (6-63)$$

The set of Equations 6-53 to 6-56 is integrated over the core volume (from 1 to 2, Figure 6.1). It is assumed that the average of the product of the density and enthalpy is a product of the averages. This is valid for well mixed regime expected during this period. Furthermore, as our intention is to compare two facilities, the approximation will not change the qualitative relationship between the time constants for the two facilities of this period. The energy equation for the solids (Equation 6-60) has also been integrated and the heat transfer at the top and the bottom of the plates has been neglected. The set of integrated balance equations are given here.

$$L_C \frac{d\langle \rho_m \rangle}{dt} + (\rho_{m2} U_{C2} - \rho_l U_{C1}) = 0 \quad (6-64)$$

$$\begin{aligned} L_C \left[\frac{d\langle \rho_m \rangle}{dt} \langle U \rangle_C + \langle \rho_m \rangle \frac{d\langle U \rangle_C}{dt} \right] \\ + (\rho_{m2} U_{C2}^2 - \rho_l U_{C1}^2) = -L_C (\rho_l - \langle \rho_m \rangle) g \\ - \left[\frac{\alpha_{C2} \rho_l \rho_g}{(1-\alpha_{C2}) \rho_{m2}} V_{gj,2}^2 \right] \\ - \left[\frac{f_{20} L_C}{2D} \rho_l U_{C1}^2 \right] \\ + K_{C1} \frac{1}{2} \rho_l U_{C1}^2 + K_{C2} \frac{1}{2} \rho_m U_{C2}^2 \end{aligned} \quad (6-65)$$

$$\begin{aligned} L_C \left[\langle H_m \rangle \frac{d\langle \rho_m \rangle}{dt} + \langle \rho_m \rangle \frac{d\langle H_m \rangle}{dt} \right] + (\rho_{m2} U_{C2} H_{m2} - \rho_l U_{C1} H_{m1}) \\ = \frac{h(\langle T_s \rangle - \langle T_c \rangle) \epsilon L_C}{A_C} - \left[\frac{\alpha_{C2} \rho_g \rho_l}{\rho_{m2}} H_{fg} V_{gj,2} \right] \end{aligned} \quad (6-66)$$

$$\rho_s C_{ps} \frac{d\langle T_s \rangle}{dt} = \langle \dot{q}_w \rangle - \frac{h(\langle T_s \rangle - \langle T_c \rangle)}{\delta_s} \quad (6-67)$$

$$\langle H_m \rangle = H_f + \langle c \rangle H_{fg} \quad (6-68)$$

$$\langle \rho_m \rangle = \langle \alpha \rangle \rho_g + (1 - \langle \alpha \rangle) \rho_l \quad (6-69)$$

$$\langle \rho_m \rangle = \langle \alpha \rangle \rho_g / \langle c \rangle \quad (6-70)$$

$$\langle H_m \rangle = (H_{C1} + H_{C2})/2 \quad (6-71)$$

$$\langle U \rangle_C = (U_{C1} + U_{C2})/2 \quad (6-72)$$

$$\rho_{m2} = \alpha_{C2} \rho_g + (1 - \alpha_{C2}) \rho_l \quad (6-73)$$

$$H_{m2} = H_f + c_2 H_{fg} \quad (6-74)$$

$$c_2 = \alpha_{C2} \rho_g / \rho_{m2} \quad (6-75)$$

$$f_{20} = f_l \left[\frac{1 + \frac{(\rho_l - \rho_g) \chi_{C2} / 2 \rho_g}{(1 + (\frac{\Delta u}{u_g} \frac{\chi_{C2}}{2}))}}{0.25} \right] \quad (6-76)$$

$$\chi_{C2} = f(c_2, V_{gj2}) \quad (6-77)$$

$$H_{C1} = H_{l,1} \quad (6-78)$$

$$\langle T \rangle_C = f(H_f, H_{l,1}) \quad (6-79)$$

The system of Equations 6-61, and 6-64 to 6-78 consists of 17 equations and 17 unknowns, $\langle T_s \rangle$, $\langle T \rangle_C$, $\langle \rho_m \rangle$, ρ_{m2} , $\langle \alpha \rangle$, α_{C2} , $\langle c \rangle$, c_2 , U_{C1} , U_{C2} , $\langle U_C \rangle$, H_{C1} , H_{C2} , $\langle H_m \rangle$, V_{gj2} , f_{20} and χ_{C2} .

Equations 6-61 and 6-64 to 6-67 have been non-dimensionalized, with the reference quantities based on fluid parameters at the beginning of this period:

$$\Theta = \frac{T - T_l}{T_{\text{sat}} - T_l}, \quad \bar{H}_m = \frac{H_m - H_l}{H_f - H_l}, \quad \bar{\rho}_m = \rho_m / \rho_r, \quad \bar{\rho}_l = \rho_l / \rho_r \quad (6-80)$$

$$\begin{aligned} \langle \bar{\rho}_m \rangle \frac{d\langle \bar{U} \rangle_C}{dt} + \left(\frac{U_r \tau_r}{L_r} \right) [\bar{\rho}_{m2} \bar{U}_{C2} (\bar{U}_{C2} - \langle \bar{U} \rangle_C) - \bar{\rho}_l \bar{U}_{C1} (\bar{U}_{C1} - \langle \bar{U} \rangle_C)] \\ = - \frac{\langle \alpha \rangle g \tau_r}{U_r} \bar{\rho}_l - \left[\frac{\alpha_{C2}}{1 - \alpha_{C2}} \frac{U_r \tau_r \bar{\rho}_l^2}{L_r} \left(\frac{\rho_g}{\rho_l} \right) \frac{\bar{v}_{gj2}}{\bar{\rho}_{m2}} \right] \\ + \left[\frac{f_C (1 + \rho_l \chi_{C2} / 2 \rho_g)}{(1 + \frac{\Delta u}{u} \frac{\chi_{C2}}{2})} \frac{L_C}{D_C} + K_{C1} \right. \\ \left. + K_{C2} \left(1 + \frac{\Delta \rho}{\rho_g} \chi_{C2}^{1.5} \right) \right] \frac{1}{2} \bar{\rho}_l \bar{U}_l^2 \frac{U_r \tau_r}{L_r} \end{aligned} \quad (6-81)$$

$$\begin{aligned} \langle \bar{\rho}_m \rangle \frac{d\langle \bar{H}_m \rangle}{dt} + \left(\frac{U_r \tau_r}{L_r} \right) [\bar{\rho}_{m2} \bar{U}_{C2} (\bar{H}_{m2} - \langle \bar{H}_m \rangle) - \bar{\rho}_l \bar{U}_{C1} (\bar{H}_{m1} - \langle \bar{H}_m \rangle)] \\ = \frac{h \epsilon \tau_r}{c_p \rho_r A_C} (\langle \theta \rangle_s - \langle \theta \rangle_c) - \frac{\alpha_C H_{fg}}{(H_f - H_l)} \frac{\tau_r U_r}{L_r} \bar{\rho}_l^2 \frac{\bar{v}_{gj2}}{\bar{\rho}_{m2}} \left(\frac{\rho_g}{\rho_l} \right) \end{aligned} \quad (6-82)$$

$$\frac{d\langle \theta_s \rangle}{dt} = \frac{\langle \dot{q} \rangle \tau_r}{\rho_s C_{ps} (T_{\text{sat}} - T_l)} + \frac{h \tau_r}{\rho_s C_{ps} \delta_s} (\langle \theta_s \rangle - \langle \theta \rangle_c) \quad (6-83)$$

$$\bar{v}_{gj} = v_{gj} / U_r \quad (6-84)$$

The non-dimensional groups obtained from the dimensionless equations are listed here.

$$G_{2,1} = \frac{U_r \tau_r}{L_r}$$

$$G_{2,2} = \rho_g / \rho_l$$

(6-85)

$$G_{2,3} = \sigma / \sigma_r$$

$$G_{2,4} = \Delta \mu / \mu_g$$

$$G_{2,5} = C_{p,r} A_c / C_{p,s} \rho_s \delta_s \epsilon$$

(Heat Capacity Ratio)

$$G_{2,6} = G_{2,1} * f_C (1 + \rho_l \chi_{C2} / 2 \rho_g) / (1 + \Delta \mu \chi_{C2} / 2 \mu_g)^{0.25} (L_C / 2 D_C)$$

$$G_{2,7} = G_{2,1} * K_{C1} / 2$$

$$G_{2,8} = G_{2,1} * K_{C2} (1 + \Delta \rho \chi_{C2}^{1.5} / \rho_g) / 2$$

$$G_{2,9} = \rho_m / \rho_r$$

$$G_{2,10} = \frac{\langle \alpha \rangle_g \tau_r}{U_r}$$

(Froude Number)

$$G_{2,11} = h \epsilon \tau_r / (C_{p,r} A_c)$$

(Stanton Number)

$$G_{2,12} = (H_f - H_l) / H_{fg}$$

(Subcooling Number)

$$G_{2,13} = k_s \tau_r / (\rho_s C_{p,s} L^2)$$

(Fourier Number)

$$G_{2,14} = \langle \dot{q} \rangle \tau_r / (\rho_s (H_f - H_l))$$

(Heat Source Number)

$$G_{2,15} = V_{gj} / U_r$$

(Drift Number)

$$G_{2,16} = \alpha_{c2}$$

The reference numbers used to evaluate the 16 groups listed in Equation 6-85 are given here:

$$L_r = L_C$$

$$U_r = U_{C1}(o) = 0.31 \text{ m/s}$$

(6-86)

$$\rho_r = \rho_l$$

$$\sigma_r = \sigma$$

6.1.2.2 Assessment of Similarity

The channel in the test and the channels in the HFBR core are geometrically very close, as can be seen from Table 6.2. Furthermore, the properties of D₂O and H₂O are also very close (<10%). Also, for the same heat flux (47,600 BTU/ft² hr), the core velocity at the beginning of this period are about the same (Equation 6.39).

$$\frac{(L_r)_{\text{Test}}}{(L_r)_{\text{HFBR}}} \approx 1$$

$$\frac{(U_r)_{\text{Test}}}{(U_r)_{\text{HFBR}}} \approx 1$$

$$\frac{(\Delta\mu/\mu_g)_{\text{Test}}}{(\Delta\mu/\mu_g)_{\text{HFBR}}} \approx 1 \quad (6-87)$$

$$\frac{(\rho_r)_{\text{Test}}}{(\rho_r)_{\text{HFBR}}} \approx 1$$

$$\frac{(\sigma_r)_{\text{Test}}}{(\sigma_r)_{\text{HFBR}}} \approx 1$$

It can be concluded that groups G_{2,2}, G_{2,3}, G_{2,4}, and G_{2,15} in Equation 6-85 will be the same in the two facilities.

Estimation of the remaining 11 groups will require approximate estimation of the exit quality. We know that at the end of this period the mixture flow rate will be zero. Therefore, during this period an average mixture flow rate is estimated.

$$W = \rho_l A_C U_{C1}(o)/2 \quad (6-88)$$

$$W((H_f - H_l) + X_{C2} H_{fg}) = q_w'' A_f \quad (6-89)$$

$$x_{C2} = \frac{q_w'' A_f - W C_{pl} (T_{sat} - T_l)}{W H_{fg}} \quad (6-90)$$

$$\alpha_{C2} = \frac{x_{C2} W / A_C \rho_g}{C_o \left(\frac{x_{C2} W}{A_C \rho_g} + \frac{(1-x_{C2}) W}{A_C \rho_l} \right) + \langle \langle V_{gj} \rangle \rangle} \quad (6-91)$$

$$\rho_{m2} = \alpha_{C2} \rho_g + (1-\alpha_{C2}) \rho_l \quad (6-92)$$

The local drift velocity and profile function, C_o , are obtained from Equation 6-61.

System of Equations 6-87 through 6-92 are solved for the HFBR and the test, and the predicted flow parameters are listed here:

<u>PARAMETER</u> # OF CHANNEL	<u>UNIT</u>	<u>HFBR</u> 532	<u>TEST (28)</u> 1
W	kg/s	14.1	0.0193
U_{C1}	m/s	0.31	0.31
c_{C2}	---	0.0049	0.0049
α_{C2}	---	0.85	0.85
x_{C2}	---	0.049	0.065

The evaluation of non-dimensional groups also needs friction factor, and the heat transfer coefficients. A friction factor is obtained from Equations 6-36 to 6-38. The heat transfer coefficient is estimated as follows [Ishii & Katoka, 1983]:

$$Nu = \frac{h D_C}{k_c}$$

$$Nu = 4.36, \quad Re < 3000 \quad (6-93)$$

where

$$Re = \rho_r U_r D_c / \mu_l \quad (6-94)$$

$$Pr = \mu_l C_p / k_c$$

The non-dimensional groups for the two facilities are summarized in Table 6.3. After comparing the magnitude of the groups for the momentum balance, it was found that the channel inlet loss ($G_{2,7}$) is not important. The channel exit losses are large due to the large quality at the exit. The test has larger exit losses than the HFBR ($G_{2,8}$). This implies that the flow will be retarded sooner in the test than in the HFBR. An estimate of the time scale for the two facilities is made by adding up groups from $G_{2,6}$ to $G_{2,10}$ except $G_{2,9}$. The sum of these groups should be equal to the unsteady inertia term in the momentum equation (Eq. 6-81). The momentum equation has been non-dimensionalized to have unsteady inertia term to be of the order of 1. Therefore, the sum of coefficients of the terms on the right hand side of the Equation 6-81 should be order of 1 for correct time scale.

$$G_{2,6} + G_{2,7} + G_{2,8} + G_{2,10} = 1 \quad (6-95)$$

$$\tau_{r, HFBR} = 0.04 \text{ s} \quad (6-96)$$

$$\tau_{r, Test} = 0.033 \text{ s} \quad (6-97)$$

The time constants for this period, based on the momentum balance, are small, and any differences in the facilities will not show up significantly in the plate temperature rise. A bounding temperature rise for this period can be estimated from the adiabatic temperature rise.

$$\left(\frac{dT_s}{dt} \right)_{adia} = \frac{q_w''}{\rho_s C_{ps} \delta_s}$$

$$(\Delta T_s)_{adia} = \frac{q'' \tau_r}{\rho_s C_{ps} \delta_s} \quad (6-98)$$

$$(\Delta T_s)_{adia, HFBR} = 78 \text{ K/s} * 0.04 \text{ s} = 3.1 \text{ K}$$

$$(\Delta T_s)_{adia, TEST} = 50 \text{ K/s} * 0.033 \text{ s} = 2.0 \text{ K}$$

The time constants for vapor generation were not considered here due to equilibrium assumption. However, a comparison of time constants in Eqs. 6-44 and 6-49 for no vapor generation and in Eqs. 6-140 and 6-141 for energy transfer to fluid indicates that the HFBR will have a shorter period than the test.

TABLE 6.3 NON-DIMENSIONAL GROUPS FOR TWO PHASE DOWNWARD FLOW PERIOD

<u>Group</u>	<u>HFBR</u>	<u>TEST</u>	<u>Comments</u>
$G_{2,1}$	$0.54 \tau_r$	$0.55 \tau_r$	
$G_{2,2}$	8.7×10^{-4}	8.7×10^{-4}	
$G_{2,3}$	1.0	1.0	
$G_{2,4}$	22	22	
$G_{2,5}$	2.92	1.95	Heat Capacity Ratio
$G_{2,6}$	$5.47 \tau_r$	$6.64 \tau_r$	Channel Friction
$G_{2,7}$	$0.053 \tau_r$	$0.127 \tau_r$	Inlet Loss
$G_{2,8}$	$3.53 \tau_r$	$5.58 \tau_r$	Exit Loss
$G_{2,9}$	0.15	0.15	Ratio of Mixture to Liquid Densities
$G_{2,10}$	$18.2 \tau_r$	$18.2 \tau_r$	1/Froude
$G_{2,11}$	$0.1 \tau_r$	$0.13 \tau_r$	Stanton
$G_{2,12}$	0.11	0.116	Subcooling
$G_{2,13}$	$2.1 \times 10^{-4} \tau_r$	$6.9 \times 10^{-5} \tau_r$	Fourcier
$G_{2,14}$	$0.27 \tau_r$	$0.1 \tau_r$	Heat Source
$G_{2,15}$	-4.4	-6.3	Drift Number
$R_{e,l}$	5381	4798	Reynolds
$P_{r,l}$	2.1	1.9	Prandtl

Unlike in the HFBR, the check valve in the test loop was not closed and so this period may last longer than estimated here for the test.

There are other differences in the two facilities, namely the heat capacity ratio ($G_{2,5}$) and the Fourier number ($G_{2,13}$). The heat capacity ratio is the ratio of the heat capacities of the liquid and solid. The HFBR has a larger value of $G_{2,5}$ than the test, implying that the decay power will go more into the liquid than the solid; therefore, causing a smaller solid temperature rise. The HFBR also has a larger Fourier number, implying that the fuel has good conductivity and any temperature rise will be conducted throughout the fuel faster than in the test section. This is important since the fuel plate may have local burnout, but its associated temperature rise will be smaller. The test observed a plate temperature rise of 7-15°F/s at the top of the channel during the flow reversal experiment and it should be smaller in the HFBR.

6.2 Reverse Flow Phase

This phase begins when the flow ceases in the channel. The channel will be voided and the large buoyancy force will initiate upward flow. The friction forces will be small near stagnation and will grow as the flow is established. The steady natural circulation will be established when the buoyancy forces match the friction forces. During this phase of transient, the liquid will be coming from the bottom reflector region. Any voiding, or bubble generation, in the core will move up and out into the liquid. There will not be a flooding situation since the flow will always be co-current.

This phase is also divided into two subperiods. The initial transient period is called the Two Phase Upflow Period and the final steady state period is called the Stable Natural Circulation Period. These two subperiods are described here.

6.2.1 Two Phase Upflow Period

This period begins at stagnation and ends when stable natural circulation is established. The channels are expected to be voided at the beginning of the period. The buoyancy forces will initiate the flow into the core. However, the rate of channel flow will depend upon the vaporization rate in the channel and the channel power. Section 6.2.2 describes the end state of this period. Those equations will be used to generate the non-dimensionalized forms of this period.

6.2.1.1 Formulation

A general formulation will include balance equations for the heated section, reflector region, and the bypass region. The heated section in the core will have two regions, the bottom part will be single phase liquid (non-boiling) region while the upper part will have two phase boiling regions. (The two phase boiling region begins when the liquid becomes saturated.) The regions are shown in Figure 6.2. Formulations for these two regions are described below.

The balance equations for the non-boiling region of the heated section are stated first. The Boussinesq assumption is used in the momentum balance

FIGURE 6.2 Heated Section Between Two Fuel Plates

for the gravity terms while the axial conductance in the energy balance for the solids have been neglected.

$$\rho_{\ell} U_{C2} A_C = \rho_{\ell} \langle U \rangle_{C1\emptyset} A_C = \rho_{\ell} U_C A_C \quad (6-99)$$

$$L_{nb} \rho_{\ell} \frac{d\langle U \rangle_{C1\emptyset}}{dt} = -(P_{nb} - P_2) - \langle \rho_{\ell} \rangle_g L_{nb} - \left[\frac{f_{C2} L_{nb}}{D_C} + K_{C2} \right] \frac{1}{2} \rho_{\ell} \langle U \rangle_{C1\emptyset} |\langle U \rangle_{C1\emptyset}| \quad (6-100)$$

$$\rho_{\ell} L_{nb} \frac{d\langle H \rangle}{dt} - \rho_{\ell} \frac{dL_{nb}}{dt} (\langle H \rangle_{C1\emptyset} - H_{nb}) = \frac{h_{1\emptyset} (\langle T_s \rangle_{1\emptyset} - \langle T \rangle_{C1\emptyset}) \epsilon L_{nb}}{A_C \rho_{\ell} U_{C2} (H_f - H_2)} \quad (6-101)$$

$$L_{nb} \rho_s C_{ps} \frac{d\langle T_s \rangle_{1\emptyset}}{dt} + \rho_s C_{ps} T_{s,nb} \frac{dL_{nb}}{dt} = \langle \dot{q} \rangle L_{nb} - h_{1\emptyset} (\langle T_s \rangle_{1\emptyset} - \langle T \rangle_{C1\emptyset}) \frac{\epsilon L_{nb}}{\delta_s} \quad (6-102)$$

Besides the balance equations, the other relationships needed are:

$$\langle U \rangle_{C1\emptyset} = (U_{C,nb} + U_{C2})/2$$

$$U_{C2} = U_{C,nb} = \langle U \rangle_{C1\emptyset} = U_C \quad (6-103)$$

$$\langle H \rangle_{C1\emptyset} = (H_{nb} + H_2)/2 \quad (6-104)$$

$$H_{nb} = H_f \quad (6-105)$$

$$\langle \rho_{\ell} \rangle = (\rho_f + \rho_{\ell})/2 \quad (6-106)$$

Equation 6-103 indicates that the velocity in the single phase region of the core is independent of location and is represented by U_C for convenience.

The balance equations for the two phase region are described here. The two phase region consists of the top of the core and the core entrance section. The fluid velocity into the core is small, so a quasi-steady formulation is used. The frictional pressure drop is computed by using a two phase multiplier [Ishii et al., 1983]. It is further assumed that the liquid at the top of the core is saturated and no condensation takes place.

$$\rho_{m1} U_{m1} - \rho_{\ell} U_{C2} = 0 \quad (6-107)$$

$$\begin{aligned} (\rho_{m1} U_{m1}^2 - \rho_{\ell} U_{C2}^2) &= -(P_6 - P_{nb}) - \langle \rho_m \rangle g (L_C - L_{nb}) \\ &\quad - \left[\frac{\alpha_1}{1-\alpha_1} \frac{\rho_g \rho_{\ell}}{\rho_{m1}} v_{gj1}^2 \right] - \left[\frac{f_C}{2D_C} \frac{(L_C - L_{nb})(1 + \Delta \rho \chi_{C1}/2\rho_g)}{(1 + \Delta \mu \chi_{C1}/2\mu_g)^{0.25}} \right. \\ &\quad \left. - \frac{1}{2} K_{C1} \left(1 + \frac{\Delta \rho}{\rho_g} \chi_{C1}^{1.5} \right) \right] \rho_{\ell} U_C^2 - \langle \rho_m \rangle_{CE} L_{CE} g \\ &\quad - \frac{f_{CE} L_{CE}}{2 D_{CE}} \frac{(1 + \Delta \rho \chi_{C1}/\rho_g)}{(1 + \Delta \mu \chi_{C1}/\mu_g)^{0.25}} \left(\frac{A_C}{A_{CE}} \right)^2 \rho_{\ell} U_C^2 \end{aligned} \quad (6-108)$$

$$\rho_{m1} U_{m1} (H_{m1} - H_f) = \frac{h_{2\phi} (\langle T_s \rangle_{2\phi} - T_{sat}) \epsilon (L_C - L_{nb})}{A_C} - \frac{\alpha_1 \rho_g \rho_{\ell}}{\rho_{m1}} H_{fg} v_{gj1} \quad (6-109)$$

The average mixture density and mixture enthalpy are defined as follows:

$$\langle \rho_m \rangle = \langle \alpha \rangle \rho_g + (1 - \langle \alpha \rangle) \rho_f \quad (6-110)$$

$$H_{m1} = H_f + c_1 H_{fg} \quad (6-111)$$

The energy balance for the solids:

$$\langle \dot{q} \rangle (L_C - L_{nb}) = \frac{h_{2\phi} (\langle T_s \rangle_{2\phi} - T_{sat}) \epsilon (L_C - L_{nb})}{\delta_s} \quad (6-112)$$

The formulation is completed by including balance equations for the bypass region and the reflector region. It is assumed that there is no heat transfer in these regions and the liquid is incompressible.

$$L_{B\phi\ell} \frac{dU_B}{dt} = (P_4 - P_5) + \rho_{\ell} g (E_5 - E_4) - \left(\frac{f_B L_B}{D_B} + K_B \right) \frac{1}{2} \rho_{\ell} U_B |U_B| \quad (6-113)$$

$$\rho_{\ell} A_B U_B = \rho_{\ell} A_R U_R \quad (6-114)$$

$$L_R \rho_\ell \frac{dU_R}{dt} = (P_4 - P_2) + \rho_\ell g(E_4 - E_2) - \left[\frac{f_R L_R}{D_R} \right] \rho_\ell U_R^2 \quad (6-115)$$

$$\rho_\ell A_R U_R = \rho_\ell A_C U_C \quad (6-116)$$

Assuming further that the temperature in the reflector and bypass region does not change during the transient:

$$\frac{dH_2}{dt} = 0 \quad (6-117)$$

Equation (6-101) can be simplified by using Equations (6-117) and (6-105):

$$\rho_\ell (\langle H \rangle_C - H_f) \frac{dL_{nb}}{dt} = - \frac{h_{10} (\langle T_s \rangle_{10} - \langle T \rangle_{C10})}{A_C} + \rho_\ell U_{C2} (H_f - H_2) \quad (6-118)$$

The momentum equations (6-100), (6-108), (6-113) and (6-115) are combined to eliminate pressure terms. The gravity terms are combined as shown in Appendix B.

$$\begin{aligned} \rho_\ell A_C I_{10} \frac{dU_C}{dt} + (\rho_{m1} U_{m1}^2 - \rho_\ell U_C^2) \\ = \langle \alpha \rangle_{C20} (\rho_\ell - \rho_g) g (L_C - L_{nb}) + g \beta \rho_\ell (T_{sat} - T_2) (L_C + L_{CE} - L_{nb} / 2) \\ + \langle \alpha \rangle_{CE} \rho_\ell g L_{CE} - \left[\frac{f_C L_{nb}}{D_C} + \left(\frac{f_B L_B}{D_B} + K_B \right) \left(\frac{A_C}{A_B} \right)^2 \right. \\ \left. + K_{C2} + \frac{f_R L_R}{D_R} \left(\frac{A_C}{A_R} \right)^2 \right] \frac{1}{2} \rho_\ell U_C |U_C| \\ - \left[\frac{f_C (L_C - L_{nb})}{D_C} \frac{(1 + \Delta \rho \chi_{C1} / 2 \rho_g)}{(1 + \Delta \mu \chi_{C1} / 2 \mu_g)^{0.25}} \right. \\ \left. + \frac{f_{CE} L_{CE}}{D_{CE}} \frac{(1 + \Delta \rho \chi_{C1} / \rho_g)}{(1 + \Delta \mu \chi_{C1} / \mu_g)^{0.25}} \left(\frac{A_C}{A_{CE}} \right)^2 \right] \rho_\ell U_C |U_C| / 2 \end{aligned}$$

$$+ K_{C1} \left(1 + \frac{\Delta p}{\rho g} x_{C1}^{1.5} \right) \rho_l U_C |U_C| / 2 - \frac{\alpha_1 \rho_l \rho_g}{(1 - \alpha_1) \rho_{ml}} v_{gj}^2 \quad (6-119)$$

$$I_{10} = \frac{L_{nb}}{A_C} + \frac{L_R}{A_R} + \frac{L_B}{A_B} \quad (6-120)$$

Other relationships are:

$$\langle T \rangle_{C10} = (T_{sat} + T_2) / 2 \quad (6-121)$$

$$\langle \alpha \rangle_{C20} = \alpha_{C1} / 2 \quad (6-122)$$

$$\rho_{ml} = \rho_{ml}(\alpha_{C1}, P) \quad (6-123)$$

$$H_{ml} = H_{ml}(c_1, P) \quad (6-124)$$

$$c_{C1} = \alpha_1 \rho_g / \rho_{ml} \quad (6-125)$$

$$x_{C1} = x_{C1}(c_{C1}, \langle \langle v_{gj} \rangle \rangle, U_{C1}) \quad (6-126)$$

Constitutive relationships for friction factors, heat transfer coefficient and drift velocity are also needed. The friction factors are obtained from Equations (6-36) through (6-38), and the drift velocity is computed from Equation (6-61).

The single phase heat transfer coefficient is obtained from Equation (6-94).

The set of balance equations (6-99) to (6-102), (6-107), (6-112), (6-118) and (6-119) are non-dimensionalized with the following reference variables:

U_{Cr} single phase velocity

U_{mr} two phase mixture velocity

L_{nbr} non boiling length

$\Delta L_{1r} = L_C - L_{nbr}$	Boiling length
$\Delta L_{2r} = L_C + L_{CE} - L_{nbr} / 2$	
ρ_{mr}	Mixture density
$\Delta T_r = T_{sat} - T_2$	Core bottom subcooling
q_r''	Reference heat flux
V_{gjr}	Reference drift velocity
$I_{l\phi r}$	Single phase region inertia
τ_r	Reference time
$\theta = (T - T_2) / (T_{sat} - T_2)$	Non-dimensional temperature

The magnitude of the above mentioned variables are needed to compare the various groups in an equation. The magnitudes of these variables have been obtained from the steady state solution as described in Section 6.2.2.

The non-dimensionalized equations are provided here. The coefficients of the dimensionless terms in the equations are shown in Table 6.4. The basic non-dimensional groups which can be combined to obtain the coefficients of dimensionless balance equations listed in Table 6.4, are shown in Table 6.5.

$$\frac{dU_C}{dt} = -G_{3,1} \bar{\rho}_{ml} \bar{U}_{ml} + G_{3,2} \bar{U}_C^2 + G_{3,3} \Delta \bar{L}_1 + G_{3,4} \Delta \bar{L}_2 + G_{3,5}$$

$$- [G_{3,6} \bar{L}_{nb} + G_{3,7}] \bar{U}_C^2 - [G_{3,8} \Delta \bar{L}_1 + G_{3,9} + G_{3,10}] \bar{U}_C^2$$

$$- G_{3,11} \bar{V}_{gj1}^2$$

(6-127)

TABLE 6.4 COEFFICIENTS OF DIMENSIONLESS EQUATIONS FOR
TWO PHASE UP FLOW PERIOD

$$G_{3,1} = \frac{1}{2} NG_{3,2} NG_{3,6}^2 NG_{3,20} NG_{3,21}$$

$$G_{3,2} = \frac{1}{2} NG_{3,20} NG_{3,21}$$

$$G_{3,3} = NG_{3,20} NG_{3,21} / NG_{3,8}$$

$$G_{3,4} = NG_{3,9} NG_{3,20} NG_{3,21}$$

$$G_{3,5} = NG_{3,20} NG_{3,21} / NG_{3,22}$$

$$G_{3,6} = \frac{1}{2} NG_{3,10} NG_{3,20} NG_{3,21}$$

$$G_{3,7} = \frac{1}{2} NG_{3,11} NG_{3,20} NG_{3,21}$$

$$G_{3,8} = \frac{1}{2} NG_{3,5} NG_{3,10} \frac{(1+NG_{3,13} - NG_{3,1}/2)}{(1+NG_{3,3} NG_{3,13})^{1/2}}$$

$$G_{3,9} = \frac{1}{2} NG_{3,12} (1 + NG_{3,13}^{1.5} / NG_{3,1}) NG_{3,20} NG_{3,21}$$

$$G_{3,10} = \frac{1}{2} NG_{3,23} \frac{(1+NG_{3,13} NG_{3,1})}{(1+NG_{3,3} NG_{3,13})^{0.25}} NG_{3,20} NG_{3,21} NG_{3,24}^2$$

$$G_{3,11} = \frac{x_1}{1-x_1} \frac{NG_{3,1}}{NG_{3,2}} NG_{3,1}^2 NG_{3,20} NG_{3,21}$$

$$G_{3,12} = 2 NG_{3,14} NG_{3,20} NG_{3,21}$$

$$G_{3,13} = 2 NG_{3,14} NG_{3,6} NG_{3,20} NG_{3,21}$$

TABLE 6.4 (CONTINUED)

$$G_{3,14} = \frac{NG_{3,16}}{NG_{3,15} NG_{3,2} NG_{3,6}}$$

$$G_{3,15} = \frac{NG_{3,7}}{NG_{3,2} NG_{3,6}}$$

$$G_{3,16} = \frac{1}{NG_{3,2} NG_{3,6}}$$

$$G_{3,17} = NG_{3,18} NG_{3,20}$$

$$G_{3,18} = NG_{3,4} NG_{3,14} NG_{3,20}$$

$$G_{3,19} = NG_{3,19}$$

$$G_{3,20} = NG_{3,17}$$

TABLE 6.5 NON-DIMENSIONAL GROUPS FOR TWO PHASE UPFLOW

$$NG_{3,1} = \rho_g / \rho_l$$

$$NG_{3,2} = \rho_{mr} / \rho_l$$

$$NG_{3,3} = \mu / \mu_g$$

$$NG_{3,4} = \rho_l C_p A_C / \rho_s C_{ps} \delta_s \epsilon$$

$$NG_{3,5} = \Delta L_{lr} / L_{nbr}$$

$$NG_{3,6} = U_{mr} / U_{Cr}$$

$$NG_{3,7} = V_{gjr} / U_{Cr}$$

$$NG_{3,8} = \rho_l U_{Cr}^2 / \alpha_l (\rho_l - \rho_g) g \Delta L_{lr}$$

$$NG_{3,9} = g \beta \Delta T_r \Delta L_{2r} / U_{Cr}^2$$

$$NG_{3,10} = f_C L_{nbr} / D_{Cr}$$

$$NG_{3,11} = K_{C2} + \left(\frac{f_B L_{Br}}{D_{Br}} + K_B \right) \left(\frac{A_{Cr}}{A_{Br}} \right)^2 + \frac{f_R L_{Rr}}{D_{Rr}} \left(\frac{A_{Cr}}{A_{Cr}} \right)^2$$

$$NG_{3,12} = K_{C1}$$

$$NG_{3,13} = X_{C1}$$

$$NG_{3,14} = \frac{h_{l0} \epsilon L_{nbr}}{A_C C_p \rho_l U_{Cr}}$$

$$NG_{3,15} = c_1$$

TABLE 6.5 (CONTINUED)

$$NG_{3,16} = \frac{h_{20} \Delta T_r \epsilon \Delta L_{1r}}{A_C \rho_l U_{Cr} H_{fg}}$$

$$NG_{3,17} = (H_f - H_2) / H_{fg}$$

$$NG_{3,18} = \frac{\dot{q}_r L_{nbr}}{\rho_s C_{ps} \Delta T_r U_{Cr}}$$

$$NG_{3,19} = \frac{h_{20} \Delta T_r}{\dot{q}_r \delta_s}$$

$$NG_{3,20} = U_{Cr} \tau_r / L_{nbr}$$

$$NG_{3,21} = L_{nbr} / A_C I_{10r}$$

$$NG_{3,22} = \rho_l U_{Cr}^2 / \alpha_{CE} (\rho_l - \rho_g) g L_{CE}$$

$$NG_{3,23} = f_{CE} L_{CE} / D_{CE}$$

$$NG_{3,24} = \left(\frac{A_C}{A_{CE}} \right)$$

$$\frac{d\bar{L}_{nb}}{dt} = \bar{U}_C G_{3,12} - G_{3,13} \left(\frac{\theta_{s,1\emptyset}^{-\theta_{c,1\emptyset}}}{\theta_f - \theta_2} \right) \quad (6-128)$$

$$\bar{\rho}_{ml} \bar{U}_{ml} = G_{3,14} \Delta \bar{L}_1 (\theta_{s,2\emptyset}^{-1}) - G_{3,15} \bar{V}_{gj1} \quad (6-129)$$

$$\bar{\rho}_{ml} \bar{U}_{ml} = G_{3,16} \bar{U}_C \quad (6-130)$$

$$\frac{d\theta_{s,1\emptyset}}{dt} + \theta_{s,nb} \frac{d\bar{L}_{nb}}{dt} = G_{3,17} \bar{q} \bar{L}_{nb} - G_{3,18} \bar{L}_{nb} (\theta_{s,1\emptyset}^{-\theta_c}) \quad (6-131)$$

$$\bar{q} = G_{3,19} (\theta_{s,2\emptyset}^{-1}) \quad (6-132)$$

$$G_{3,20} = C_p (T_{sat} - T_2)/H_{fg} \quad (6-133)$$

6.2.1.2 Assessment of Similarity

The fluid conditions in these facilities are described by 24 groups listed in Table 6.5 and the coefficients of dimensionless terms of the balance equations are listed in Table 6.4. The reference quantities for evaluating these groups are given in Section 6.2.2.2. The reference variables are different for two facilities implying that facilities will have different end state for this period even though both have the same power and start from the same initial state. Therefore, the flow parameters will also differ during this period.

Tables 6.6 and 6.7 summarize the values of the non-dimensional groups and the coefficients of the non-dimensional balance equations for this period for two facilities. As the final stable natural convection states are different for the two facilities, the nondimensional groups in Tables 6.6 and 6.7 show the difference between the facilities. A comparison of coefficients of the non-dimensional balance equations for the two facilities (Table 6.7) indicate that the facilities will not behave similarly. The first eleven groups are from the momentum balance equation. The dominant terms are the buoyancy terms ($G_{3,5}$) due to the voiding in the core entrance region (core top) and the losses in the bypass region and the junction at the core bottom ($G_{3,7}$). The buoyancy due to voiding in the core ($G_{3,3}$) is small for the HFBR but an order of magnitude larger in the test. The other differences in the behavior of two facilities can be seen from the coefficients of the dimensionless energy equations ($G_{3,14}$ and $G_{3,15}$). The phase change and drift velocity effect is larger in the test.

TABLE 6.6 NON-DIMENSIONAL GROUPS FOR TWO PHASE UPFLOW

<u>Group</u>	<u>HFBR</u>	<u>TEST</u>	<u>Comments</u>
NG3,1	0.0009	0.0009	
NG3,2	0.58	0.31	
NG3,3	22.1	22.1	
NG3,4	2.95	1.95	Heat Capacity Ratio
NG3,5	0.017	0.16	Ratio of Boiling to Non-Boiling Length
NG3,6	1.7	3.2	
NG3,7	1.8	8.2	Drift Number
NG3,8	3.904	0.23	Froude Number, Channel
NG3,9	1.9	3.04	Richardson Number, Channel
NG3,10	0.96	0.68	Channel Friction
NG3,11	34.18	65.9	Single Phase Path Friction
NG3,12	1	1	Loss Coefficient at Top of Core
NG3,13	0.002	0.018	Quality at Top of Core
NG3,14	0.2	0.26	Single Phase Stanton Number
NG3,15	$0.0006 h_{2\phi}$	$0.002 h_{2\phi}$	Exit Vapor Mass Fraction
NG3,16	$0.0007 h_{2\phi}$	$0.008 h_{2\phi}$	Phase Change Number
NG3,17	0.104	0.11	Subcooling Number
NG3,18	2.9	2	Heat Source Number
NG3,19	$0.37 \tau_r$	$0.41 \tau_r$	
NG3,20	0.48	0.50	Ratio of Time Scale and Residence Time
NG3,21	0.92	0.9	Fraction of Inertia due to Non-Boiling Length
NG3,22	0.060	0.032	Froude Number for Core Entrance
NG3,23	0.007	0.06	Core Entrance Friction

TABLE 6.7 COEFFICIENTS OF BALANCE EQUATIONS FOR TWO PHASE UPFLOW

<u>Coefficient</u>	<u>HFBR</u>	<u>TEST</u>	<u>Comments</u>
$G_{3,1}$	$0.8 \tau_r$	$1.46 \tau_r$	
$G_{3,2}$	$0.44 \tau_r$	$0.45 \tau_r$	
$G_{3,3}$	$0.145 \tau_r$	$1.95 \tau_r$	Buoyancy, Core
$G_{3,4}$	$0.85 \tau_r$	$1.38 \tau_r$	Buoyancy (Richardson No.)
$G_{3,5}$	$7.48 \tau_r$	$14.0 \tau_r$	Buoyancy, Core Entrance-Top
$G_{3,6}$	$0.215 \tau_r$	$0.15 \tau_r$	Losses in 1Ø Core Region
$G_{3,7}$	$7.7 \tau_r$	$14.9 \tau_r$	Losses due Bypass, Reflector to Entrance (bottom)
$G_{3,8}$	$0.009 \tau_r$	$0.26 \tau_r$	Losses Due to Boiling Region in Core
$G_{3,9}$	$0.24 \tau_r$	$0.84 \tau_r$	Top of Core or Inlet Fric.
$G_{3,10}$	$0.0015 \tau_r$	$0.01 \tau_r$	Core Entrance-Top-Friction
$G_{3,11}$	$0.002 \tau_r$	$0.19 \tau_r$	Drift Effect
$G_{3,12}$	$0.97 \tau_r$	$1.0 \tau_r$	
$G_{3,13}$	$0.20 \tau_r$	$0.26 \tau_r$	
$G_{3,14}$	$1.04 \tau_r$	$4.1 \tau_r$	Phase Change, Energy Equation
$G_{3,15}$	$1.8 \tau_r$	$8.2 \tau_r$	Drift Effect, Energy Equation
$G_{3,16}$	$1.0 \tau_r$	$1.0 \tau_r$	
$G_{3,17}$	$1.41 \tau_r$	$1.0 \tau_r$	
$G_{3,18}$	0.29	0.25	
$G_{3,19}$	0.37	0.4	
$G_{3,20}$	0.1	0.11	Bottom Subcooling

The differences in the facilities can be easily understood from the comparison of non-dimensional groups (NG3,1) of Table 6.6. The table indicates that the HFBR has a larger fluid thermal capacity than the test relative to the thermal capacity of the solids. This implies that the larger fraction of the power will go to the fluid in the HFBR than in the test and, therefore, the solid heatup rate will be slower in the HFBR. Comparison of NG3,7 indicates that there is a larger drift velocity at the top of the core in the test than in the HFBR which is consistent with larger volume flux in the test. The test has larger volume flux due to larger exit quality. The drift velocity is dominated by the profile terms so it is significantly affected by the volume flux. A comparison of NG3,8 and NG3,22, indicates that the Froude numbers are smaller in the test than the HFBR, which is consistent with the larger quality and void fraction in the test. The smaller Froude number implies that the test has larger buoyancy forces to match the larger friction forces. The Richardson number (NG3,9) represents the buoyancy forces due to liquid density change and, as expected, much smaller than the inverse of Froude number.

Comparison of NG3,13 indicates that the HFBR has smaller exit quality than in the test, which is consistent with larger reference velocity for the HFBR. Similar groups NG3,16 and NG3,18 can be explained. The phase change number NG3,16 which represents the fraction of inlet flow vaporizing in the channel, is smaller in the HFBR than in the test, and is consistent with the larger flow rate in the HFBR.

Table 6.7 shows the coefficients for the balance equations. We will estimate time constants for the momentum equation and also for heating the subcooled liquid to saturation conditions in the channel. The larger of the two time constants will control the transient. The dominant terms in the momentum equation (G3,1 to G3,11) are the buoyancy due to voiding and friction loss in the bypass region. As expected, the test will have much larger value of these terms than the HFBR due to a larger voided region in the test. An estimate of time can be made by looking at the momentum balance at half the stable natural circulation flow as it represents an average condition for this period of the transient.

$$U_r = 0.122 \text{ m/s, Test}$$

$$U_r = 0.138 \text{ m/s, HFBR}$$

The rate of change of core velocity is estimated from the momentum balance (Eq. 6-119) for the test.

$$\frac{dU_c}{dt} = \frac{2211 \text{ N/m}^2}{2350 \text{ m}^{-1} \times \rho_l \times 0.000126 \text{ m}^2} = 7.56 \text{ m/s}^2 \quad (6-134)$$

$$\tau_{\text{test}} = \frac{0.244 \text{ m/s}}{7.56 \text{ m/s}^2} = 0.032 \text{ s} \quad (6-135)$$

Similarly for the HFBR:

$$\frac{dU_C}{dt} = \frac{2743 \text{ N/m}^2}{3.95 \text{ m}^{-1} \times \rho_l \times 0.0836 \text{ m}^2} = 7.58 \text{ m/s}^2 \quad (6-136)$$

$$\tau_{\text{HFBR}} = \frac{0.276 \text{ m/s}}{7.58 \text{ m/s}^2} = 0.036 \text{ s} \quad (6-137)$$

These estimates indicate that the time constant of momentum balance for the two facilities are small. An estimate of time constant to heat up incoming liquid is made as follows:

$$\frac{dT_l}{dt} (\rho_s C_{ps} \delta_s + \rho_l A_C L_C) = q'' \epsilon L_C \quad (6-138)$$

where the first term in the bracket is the heat capacity of solid and the second term is the heat capacity of the fluid.

So the time to reach saturation conditions are estimated.

$$\tau = \frac{(T_{\text{sat}} - T_2) (\rho_s C_{ps} \epsilon \delta_s + \rho_l C_{pl} A_C)}{q'' \epsilon}$$

$$\tau = \frac{\Delta T_r \rho_l C_{pl} A_C (1 + 1/NG4)}{q'' \epsilon} \quad (6-139)$$

$$\tau_{\text{test}} = 2.92 \text{ s} \quad (6-140)$$

$$\tau_{\text{HFBR}} = 2.78 \text{ s} \quad (6-141)$$

The times will be longer than shown above as some of the energy from the wall is convected with the fluid. However, for comparison purposes, it can be concluded that the thermal response will control the timing and the time to reach stable natural circulation will be longer for the test than the HFBR.

The observation from the test indicated that it took about ten seconds (Run 28) to reach steady conditions. The HFBR will take less time than the test for similar conditions. This conclusion is supported by a comparison of the non-dimensional group NG4 which is the ratio heat capacity of the fluid to

the solids. In the case of the HFBR, larger fraction of the core power will go to the fluid than in the test.

6.2.2 Stable Natural Circulation Period

This is the final period of the transient and in this period buoyancy forces balance the friction forces in the flow path.

6.2.2.1 Formulation

The set of steady state balance equations are obtained from Equations (6-107) to (6-129):

$$\begin{aligned}
 & \rho_l U_C^2 (1 - \rho_l / \rho_m) \\
 & = \langle \alpha \rangle \rho_l g (L_C - L_{nb}) + \beta \rho_l g (T_{sat} - T_2) (L_C + L_{CE} - L_{nb} / 2) + \langle \alpha \rangle_{CE} \rho_l g L_{CE} \\
 & - \left[\frac{f_C L_{nb}}{D_C} + K_{C2} + \left(\frac{f_B L_B}{D_B} + K_B \right) \left(\frac{A_C}{A_B} \right)^2 + \frac{f_R L_R}{D_R} \left(\frac{A_C}{A_R} \right)^2 \right] \frac{1}{2} \rho_l U_C^2 \\
 & - \left[\frac{f_C (L_C - L_{nb})}{D_C} \frac{(1 + \Delta \rho \chi_{C1} / 2 \rho_g)}{(1 + \Delta \mu \chi_{C1} / 2 \mu_g)^{0.25}} + K_{C1} \left(1 + \frac{\Delta \rho}{\rho_g} \chi_{C1}^{1.5} \right) \right. \\
 & \left. + \frac{f_{CE} L_{CE}}{D_{CE}} \frac{(1 + \Delta \rho \chi_{C1} / \rho_g)}{(1 + \Delta \mu \chi_{C1} / \mu_g)^{0.25}} \right] \frac{1}{2} \rho_l U_C^2 - \frac{\alpha_1 \rho_l \rho_l}{(1 - \alpha_1) \rho_{ml}} \frac{V_{gj}^2}{g} \quad (6-142)
 \end{aligned}$$

In steady state, the heat generated in the solid is convected to the fluid, so from Equations (6-102) and (6-118), neglecting the axial conduction we obtain an expression for L_{nb} :

$$L_{nb} = \frac{(H_f - H_2) \rho_l U_C D_C}{4 \dot{q}''} \quad (6-143)$$

From mass balance we obtain:

$$\rho_{ml} U_{ml} = \rho_l U_C \quad (6-144)$$

The drift velocity is obtained as:

$$V_{gj1} = (C_o - 1) j_1 + \langle\langle V_{gj} \rangle\rangle \quad (6-145)$$

where C_o and $\langle\langle V_{gj} \rangle\rangle$ are obtained from Equation 6-61. The other required relationships are described here.

$$X_1 = \frac{4 q'' (L_C - L_{nb})}{\rho_\ell U_C H_{fg} D_C} \quad (6-146)$$

$$j_1 = j_{g1} + j_{\ell 1} \quad (6-147)$$

$$U_{g1} = C_o j_1 + \langle\langle V_{gj} \rangle\rangle \quad (6-148)$$

$$j_{g1} = X_1 \rho_\ell U_C / \rho_g \quad (6-149)$$

$$j_{\ell 1} = (1 - X_1) \rho_\ell U_C / \rho_\ell \quad (6-150)$$

$$\alpha_1 = j_{g1} / U_{g1} \quad (6-151)$$

$$\rho_{m1} = \alpha_1 \rho_g + (1 - \alpha_1) \rho_f \quad (6-152)$$

$$\alpha = \alpha_1 / 2 \quad (6-153)$$

$$H_{m1} = c_1 H_g + (1 - c_1) H_f \quad (6-154)$$

$$H_2 = \text{known, boundary conditions} \quad (6-155)$$

There are 14 equations (6-154 to 6-167) and 14 unknowns, U_C , U_{m1} , U_{g1} , $j_{\ell 1}$, V_{gj1} , α_1 , α , X_1 , ρ_{m1} , H_{m1} , H_2 , L_{nb} , and j_1 . The single phase friction factors are obtained from Equations (6-36) through (6-38). This completes the formulation.

The above mentioned equations have been non-dimensionalized using reference lengths, diameters, areas, densities, velocity, subcooling and power. The resulting equations are provided here.

$$\begin{aligned}
-\frac{1}{2} \bar{\rho}_\ell \bar{U}_C^2 \left(1 - \frac{\bar{\rho}_\ell}{\bar{\rho}_m}\right) &= \frac{\alpha \rho_\ell L_{Cr}}{U_r^2} (\bar{L}_C - \bar{L}_{nb}) + \frac{\beta g \Delta T_r L_{Cr}}{U_r^2} (\bar{L}_C + \bar{L}_{CE} - \bar{L}_{nb}/2) \\
&+ \frac{\alpha_{CE} \rho_\ell L_{CE} L_{Cr}}{U_r^2} - \frac{1}{2} \left[\frac{f_C L_{nbr}}{D_{Cr}} - K_{C2} + \left(\frac{f_B L_{Br}}{D_{Br}} + K_B \right) \left(\frac{A_{Cr}}{A_{Br}} \right)^2 \right. \\
&+ \left. \frac{f_R L_{Rr}}{D_{Rr}} \left(\frac{A_{Cr}}{A_{Rr}} \right)^2 \right] \bar{\rho}_\ell \bar{U}_C^2 \\
&- \frac{1}{2} \left[\frac{f_C (L_{Cr} - L_{nbr})}{D_{Cr}} \frac{1 + \Delta \rho \chi_{C1} / 2 \rho_g}{(1 + \chi_{C1} \Delta \mu / 2 \mu_g)^{0.25}} + K_{C1} \left(1 + \frac{\Delta \rho}{\rho_g} \chi_{C1}^{1.5} \right) \right. \\
&+ \left. \frac{f_{CE} L_{CEr}}{D_{CEr}} \frac{(1 + \Delta \rho \chi_{C1} / \rho_g)}{(1 + \Delta \mu \chi_{C1} / \mu_g)^{0.25}} \right] \frac{1}{2} \bar{\rho}_\ell \bar{U}_C^2 - \frac{\alpha_1 \rho_g \rho_\ell v_{gj}^2}{(1 - \alpha_1) \rho_\ell^2 \bar{\rho}_m} \quad (6-156)
\end{aligned}$$

$$\bar{L}_{nb} = \frac{C_{pl} \Delta T_r \rho_r U_r D_{Cr}}{4 q''} \bar{\rho}_\ell \bar{U}_C \Delta \bar{T} \quad (6-157)$$

$$\bar{V}_{gj} = v_{gj} / U_r \quad (6-158)$$

$$\chi_{C1} = \frac{4 q'' (L_{Cr} - L_{nbr})}{\rho_r U_r H_{fg} D_{Cr} \bar{\rho}_\ell \bar{U}_C} \quad (6-159)$$

The non-dimensional group is obtained from the above set of equations and are listed here:

$$NG_{4,1} = \frac{U_r^2}{\alpha g L_r}$$

Froude Number

$$NG_{4,2} = \frac{\beta g \Delta \tau_r L_{Cr}}{U_r^2}$$

$$NG_{4,3} = \frac{f L_{nbr}}{D_{Cr}} + \frac{f(L_{Cr} - L_{nbr})}{D_{Cr}} \left(\frac{1 + \Delta \rho \chi_1 / 2 \rho_g}{(1 + \chi_1 \Delta \mu / \mu_g)} \right) + K_{C1} \left(1 + \frac{\Delta \rho}{\rho_g} \chi_{c1} \right)^{1.5} + K_{C2} \\ + \frac{f_{CE} L_{CEr}}{D_{CEr}} \frac{(1 + \Delta \rho \chi_1 / \rho_g)}{(1 + \chi_1 \Delta \mu / \mu_g)^{0.25}}$$

$$NG_{4,4} = \left(\frac{f_B L_{Br}}{D_{Br}} + K_B \right) \left(\frac{A_{Cr}}{A_{Br}} \right)^2 + \frac{f_R I_{Rr}}{D_{Rr}} \left(\frac{A_{Cr}}{A_{Br}} \right)^2 \quad (6-160)$$

$$NG_{4,5} = \rho_g / \rho_l$$

$$NG_{4,6} = \Delta \mu / \mu_g$$

$$NG_{4,7} = \frac{C_p \Delta T_r}{H_{fg}}$$

Subcooling Number

$$NG_{4,8} = \frac{4 q'' L_r}{\rho_r U_r H_{fg} D_{Cr}}$$

Phase Change Number

$$NG_{4,9} = v_{gjr} / U_r$$

Drift Number

$$NG_{4,10} = L_{CEr} / L_{Cr}$$

Ratio of Core Entrance and Core Lengths

$$NG_{4,11} = \alpha_{CE}$$

Core Entrance (Top) Void Fraction

6.2.2.2 Assessment of Similarity

The non-dimensional groups listed in Equation (6-160) are evaluated for the HFBR and the test. The reference parameters such as U_r are obtained from the solution of equations and the geometric parameters are obtained from Table 6.2. The important parameters are given here:

<u>PARAMETER</u>	<u>UNITS</u>	<u>HFBR</u>	<u>SET</u>
U_r	m/s	0.276	0.244
U_{ml}	m/s	0.47	0.78
L_{nb}	m	0.57	0.48
x_1		0.0017	0.018
$\langle \alpha \rangle_{2\phi}$		0.21	0.34
q''	kW/m ²	147.2	147.2
L_C	m	0.578	0.56
ΔT_{sub}	K	55	60

For the same power, the test has smaller velocity, larger quality and larger two phase region in the channel than in the HFBR. Table 6.8 summarizes the non-dimensional groups. The flows are not similar. A comparison of NG4,3 and NG4,4 indicates that the test has much larger friction loss than the HFBR. However, the test also has larger buoyancy force (smaller Froude number) than the HFBR, but it is not enough to overcome additional friction in the test, resulting in smaller velocity and larger quality in the test. This comparison indicates that the test is more likely to burn out than the HFBR.

The analysis was also performed for two smaller power levels and the results are given here for the HFBR and the test.

Power	<u>HFBR</u>		<u>TEST</u>	
	U_r	$\langle \alpha \rangle_{2\phi}$	U_r	$\langle \alpha \rangle_{2\phi}$
kW/m ²	m/s		m/s	
147.2	0.276	0.21	0.244	0.34
120.2	0.231	0.21	0.214	0.32
60.1	0.113	0.0	0.114	0.211

As expected, the analysis showed the flow rate increased with the power and then decreased. The burnout conditions have been observed when the flow is decreasing with the increase in power. The HFBR will always have higher flow rates than the test whenever there is boiling in the channel. Therefore, the test is more likely to go to burnout conditions than the HFBR. The CHF increases with flow rate as shown in Figure 6.3 [Mishima, et al., 1985].

TABLE 6.8 NON-DIMENSIONAL GROUPS FOR STABLE NC PERIOD

<u>Coefficient</u>	<u>HFBR</u>	<u>SET</u>	<u>Comments</u>
NG _{4,1}	0.06	0.03	Froude
NG _{4,2}	1.76	2.6	Richardson
NG _{4,3}	2.6	6.1	Channel Friction
NG _{4,4}	33.6	65.4	Bypass Path Friction
NG _{4,5}	0.0009	0.0009	Density Ratio
NG _{4,6}	22	22	Viscosity Ratio
NG _{4,7}	0.104	0.11	Subcooling Number
NG _{4,8}	0.106	0.13	Phase Change
NG _{4,9}	2.0	8.8	Drift Number
NG _{4,10}	0.57	0.63	Ratio of Heights of Core Entrance and Core
NG _{4,11}	0.42	0.54	Core Entrance Void Fraction
Re	4835	3740	Reynolds Number

FIGURE 6.3 Critical Heat Flux for the Test Section Heated from Two Opposite Sides

Run 30 in the test had burnout at power of 151.3 KW/m^2 . However, the transient behavior indicated that the flow conditions were probably close to an instability boundary and there were oscillations in the plate temperature before temperature excursion began. The dimensionless group controlling the stable behavior are phase change number, inlet friction coefficient and subcooling. A comparison of these groups indicates that the HFBR has the same core inlet friction coefficient, but has a smaller phase change number (with the difference of ~20%) which makes flow more stable in the HFBR. However, the subcooling was higher in the test than in the HFBR, but the difference is less than 1%. Therefore, the HFBR flow is expected to be relatively stable in comparison to the test and less likely to go into burnout than the test.

7. CONCLUSIONS

The hydraulic behavior of two facilities for a loss of power accident (LOPA) with identical channel powers has been analyzed. The hydraulic response has been divided into four periods and the similarity between the HFBR and the test has been assessed for each of these periods. These four periods are the Coastdown Period, the Two Phase Downward Flow Period, the Two Phase Upflow Period, and the Stable Natural Circulation Period, respectively.

Both the test procedure and the set up were different from the HFBR for the initial Coastdown Period. The loop flow is stopped with a check valve in the HFBR while it was allowed to continue in the test. In this period, the downflow into the core slows down faster in the HFBR than in the test. The second period is the Two Phase Downward Flow Period. During this period, the flow is opposed by both the buoyancy and the friction forces. It was shown that starting from the same core velocities, the flow will slow down faster in the HFBR than in the test. Therefore, it is concluded that as the flow reversal did take place in the test, the HFBR will also have flow reversal and will have it sooner than the test.

The remaining two periods have two phase upflow. In the third period, namely the Two Phase Upflow Period, the flow is accelerated by the buoyancy forces and opposed by the friction forces. It was found that the thermal conditions will dominate the timing and the HFBR will take less time than the test to develop fluid conditions needed to establish stable natural circulation.

The flow conditions in the fourth period, Stable Natural Circulation Period, indicate that the HFBR will have more flow than the test for the same power. The cause of this behavior is the friction in the flow path which affects flow rate and, consequently, the exit quality. As was shown in Figure 6.3, the larger flow will result in a larger critical heat flux. The result is that the HFBR will reach CHF conditions at higher power than the test section.

The power in the test (147.2 kW/m^2) is greater than the decay power in the hottest channel (120 kW/m^2) of the HFBR (from an initial operating power of 60 MW) 60 seconds after scram. The test successfully negotiated flow reversal without burnout. It has been shown that the HFBR will reside for a shorter time period in the flow reversal event and will have larger flows than the test during natural circulation. Therefore, it is concluded that the HFBR hottest channel can also successfully go through flow reversal at a decay power of at least 147.2 kW/m^2 , 60 seconds after scram.

It should be noted that the arguments presented in this similarity study do not account for the dissolved He effect since it was not modeled in the experiment. Furthermore, the important runs in the test were conducted with only a single channel which removed parallel channel effects from the results. These two effects have not been discussed in this report since they were not part of the experiment and cannot be addressed in the context of this scaling analysis.

8. REFERENCES

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9. NOMENCLATURE

A	Area
C	Specific Heat
D	Hydraulic Diameter
E	Elevation
f	Friction Factor
F	Friction Number (Equation 91)
F_B	Friction Number for Bypass Flow
F_C	Core Entrance/Exit Friction Number
F_{ch}	Channel Friction Number
F_L	Friction Number for Loop (Equation 6-4)
F_R	Reflector Friction Number
G_i	Non-Dimensional Group for Coast Down Period
g	Accelerator due to Gravity
h	Enthalpy and Heat Transfer Coefficient
H	Enthalpy and also used as Henry's Constant in Section 4.1
I	Fluid Inertia
k	Thermal Conductivity
K	Loss Coefficients
L	Length
ΔL_1	$L_c - L_{nb}$
ΔL_2	$L_c + L_{CE} - L_{nb}/2$
NG	Nondimension Numbers
Nu	Nusselt Number
P	Pressure

9. NOMENCLATURE (Continued)

Q_1	Volume Flow Rate
q''	Heat Flux
$\dot{q}$	Heat generation rate in the solids
Re	Reynolds Number
St	Stanton Number
T	Temperature of fluids
T_s	Temperature of solids
t	Time
U	Velocity
V	Volume
V_{gj}	Drift Velocity
$\langle\langle V_{gj} \rangle\rangle$	Local Drift Velocity
W	Mass Flow Rate
X_{He}	Mole Fraction of Helium in Solution
α	Void Fraction
β	Liquid Expansion Coefficient
δ	Fuel Plate Thickness
ϵ	Perimeter
μ	Viscosity
ρ	Density
σ	Surface Tension
x	Quality

9. NOMENCLATURE (Continued)

Subscript

adia	Adiabatic	1Ø single phase 2Ø two phase
B	Bypass Flow	
c	Coolant	
C	Core	
CE	Core Exit	
CE	Core Entrance	
Ch	Channel	
CHF	Critical Heat Flux	
Ci	Core Inlet	
e	Exit	
ELB	Elbow	
Fr	Froude	
g	Steam	
L	Loop	
lam	Laminar	
n	End of the Transient	
nb	Location of End of Non Boiling Region	
P	Pressure	
PCH	Phase Change	
R	Reference	
r	Reflector	
s	Solid	
Sat	Saturation	
Sub	Subcooled	

9. NOMENCLATURE (Continued)

tr Turbulent

v Valve

APPENDIX A

Procedure of Combining Bypass Flows for HFBR

A.1 Introduction

The HFBR has four bypass flow valves and leakage paths around the control rods (blades and shaft). Both types of flow paths provide an alternate path to the coolant. During the coolant down flow phase, some of the coolant bypasses the core and flows through the bypass flow valves and the leakage paths. During the coolant up flow phase, natural circulation is established, with the coolant flowing up in the channel and flow down through the bypass flow valve and the leakage path.

The similarity analysis presented in the main report requires a combined representation of the bypass flow. This appendix describes the procedure used to combine the flows.

A.2 Procedure

The bypass flow valve and the leakage flow paths connect the core inlet to the top of the side reflector region as shown in Figure 2.2. As the flow is single phase and adiabatic, only mass and momentum balances are needed.

$$Q_B = A_{BP} U_{BP} + A_{BV} U_{BV} \quad (A-1)$$

$$\rho L_{BP} \frac{d U_{BP}}{dt} = - (P_3 - P_1) + \frac{1}{2} K_{BP} \rho U_{BP}^2 \quad (A-2)$$

$$\rho L_{BV} \frac{d U_{BV}}{dt} = - (P_3 - P_1) + \frac{1}{2} K_{BV} \rho U_{BV}^2 \quad (A-3)$$

where, Q_B is the total bypass volume flow rate, A_{BP} , L_{BP} , U_{BP} , K_{BP} are the area, length, velocity and the loss coefficient of the leakage path, and A_{BV} , L_{BV} , U_{BV} , K_{BV} are the area, length, velocity and the loss coefficient of the bypass flow valves. The flow paths are combined and the area, length, velocity and the loss coefficient are represented by A_B , L_B , U_B , and K_B . The combined system of equations is as follows:

$$Q_B = A_B U_B \quad (A-4)$$

$$\rho L_B \frac{d U_B}{dt} = - (P_2 - P_1) + \frac{1}{2} K_B \rho U_B^2 \quad (A-5)$$

where

$$A_B = A_{BP} + A_{BV} \quad (A-7)$$

$$L_B = \left(\frac{A_B L_{BV}}{A_{BV}} \right) / \left(1 + \frac{A_{BP} L_{BV}}{A_{BV} L_{BP}} \right) \quad (A-6)$$

$$A_B = A_{BP} + A_{BV} \quad (A-7)$$

$$K_B = \frac{\frac{K_{BP} U_{BP}^2 A_{BP}}{L_{BP}} + \frac{K_{BV} U_{BV}^2 A_{BV}}{L_{BV}}}{\frac{A_{BV}}{L_{BV}} \left(1 + \frac{A_{BP} L_{BV}}{A_{BV} L_{BP}} \right) U_B^2} \quad (A-8)$$

It is assumed that the ratio of velocities in the leakage path and the bypass flow valve remains constant and can be estimated from the steady state equations (Equation A-2, A-3).

$$r = \frac{U_{BP}}{U_{BV}} = \sqrt{\frac{K_{BV}}{K_{BP}}} \quad (A-9)$$

$$U_{BV} = \frac{A_B U_B}{A_{BV} + r A_{BP}} \quad (A-10)$$

$$U_{BP} = \frac{A_B U_B r}{A_{BV} + r A_{BP}} \quad (A-11)$$

Equations A-9 to A-11 are substituted into Equation A-8 to obtain combined coefficient:

$$K_B = \left(\frac{A_B^2}{A_{BV} + r A_{BP}} \right) \left(K_{BV} + \frac{K_{BP} A_{BP} L_{BV} r^2}{A_{BV} L_{BP}} \right) / \left(1 + \frac{A_{BP} L_{BV}}{A_{BV} L_{BP}} \right)$$

$$K_B = K_{BV} (A_B / (A_{BV} + r A_{BP}))^2 \quad (A-12)$$

A.3 Estimation of Combined Variables for HFBR

The loss coefficients, area, and lengths for the bypass flow valve and the leakage path are available from HFBR FSAR and memorandums.

$$K_{BV} = 5.5, A_{BV} = 0.02 \text{ m}^2, L_{BV} = 0.019 \text{ m}$$

$$K_{BP} = 2.67, A_{BP} = 0.01 \text{ m}^2, L_{BP} = 0.0127 \text{ m}$$

$$r = 1.44 \quad (A-13)$$

The combined variables are obtained from Equations A-6, A-7, and A-12.

$$A_B = 0.03 \text{ m}^2 \quad (A-14)$$

$$L_B = 0.0163 \text{ m}^2 \quad (A-15)$$

$$K_B = 4.33 \quad (A-16)$$

These values will be used for the HFBR in Sections 6.1.4 and 6.1.5.

APPENDIX B

Combining Gravity Terms for Loop Momentum Balance

$$\begin{aligned}
 & - \langle \rho_\ell \rangle_{nb} g L_{nb} - \langle \rho_m \rangle_C g (L_C - L_{nb}) - \langle \rho_m \rangle_{CE} g L_{CE} + \rho_\ell g (L_C + L_{CE}) \\
 & = L_{nb} g (\rho_\ell - \langle \rho_\ell \rangle_{nb}) + (L_C - L_{nb}) g (\rho_\ell - \langle \rho_m \rangle_C) + L_{CE} g (\rho_\ell - \langle \rho_m \rangle_{CE})
 \end{aligned}$$

$$\langle \rho_\ell \rangle_{nb} = (\rho_\ell + \rho_f) / 2$$

$$\langle \rho_m \rangle = \rho_f - \langle \alpha \rangle (\rho_f - \rho_g) = \rho_\ell - \langle \alpha \rangle (\rho_\ell - \rho_g) - (1 - \langle \alpha \rangle) (\rho_\ell - \rho_f)$$

$$\rho_f - \rho_\ell = \beta \rho_\ell (T_2 - T_{sat})$$

$$\begin{aligned}
 \text{Gravity Terms} &= L_{nb} g \left(\frac{\rho_\ell - \rho_f}{2} \right) + (L_C - L_{nb}) g (\rho_\ell - \rho_\ell + \langle \alpha \rangle_C (\rho_\ell - \rho_g) + (1 - \langle \alpha \rangle_C) (\rho_\ell - \rho_f)) \\
 &\quad + L_{CE} g (\rho_\ell - \rho_\ell + \langle \alpha \rangle_{CE} (\rho_\ell - \rho_g) + (1 - \langle \alpha \rangle_{CE}) (\rho_\ell - \rho_f))
 \end{aligned}$$

$$= g \beta \rho_\ell (T_{sat} - T_2) (L_C (1 - \langle \alpha \rangle_C) - \frac{L_{nb}}{2} (1 - 2 \langle \alpha \rangle_C)) + \langle \alpha \rangle_C (\rho_\ell - \rho_g) g (L_C - L_{nb})$$

$$+ g \beta \rho_\ell (T_{sat} - T_2) (L_{CE} (1 - \langle \alpha \rangle_{CE})) - \langle \alpha \rangle_{CE} (\rho_\ell - \rho_g) g L_{CE}$$

$$= g (L_C - L_{nb}) \langle \alpha \rangle_C [(\rho_\ell - \rho_g) - \beta \rho_\ell (T_{sat} - T_2)] + g \beta \rho_\ell (T_{sat} - T_2) (L_C + L_{CE} - \frac{L_{nb}}{2})$$

$$+ g L_{CE} \langle \alpha \rangle_{CE} [(\rho_\ell - \rho_g) - \beta \rho_\ell (T_{sat} - T_2)]$$

$$\text{As, } (\rho_\ell - \rho_g) \gg \beta \rho_\ell (T_{sat} - T_2)$$

$$\begin{aligned}
 \text{Gravity Term} &= g (L_C - L_{nb}) \langle \alpha \rangle_C (\rho_\ell - \rho_g) + g \beta \rho_\ell (T_{sat} - T_2) (L_C + L_{CE} - \frac{L_{nb}}{2}) \\
 &\quad + g L_{CE} \langle \alpha \rangle_{CE} (\rho_\ell - \rho_g)
 \end{aligned}$$

APPENDIX C

Paul Tichler's response to a question about the similarity of the inertia effects in the 1963 test facility and the HFBR*

*Letter from Mike Brooks to Dave Lanning, dated April 11, 1988, concerning the inertial effects match between the 1963 test facility and the HFBR.

Question

In the report describing the flow reversal tests, "Experimental Evaluation of the HFBR Emergency Cooling System" by Tichler and Hill (April, 1963), it is stated on page 7 that the "flow areas in the upper, lower, and side reflector and the lower shroud" were not closely matched. This brings up a question of matching the inertial effects around the flow loop. A mismatch can affect the time of reversal and may have some effect on the heat flux and combined adiabatic temperature rise rate (ATRR) limits that were derived from the experiments. Have you reviewed these tests relative to the inertial effects? In general, we would like to review the basis for dynamic simulation of the test loop and the reactor to confirm that the limits established by these tests are applicable to the reactor.

Response

We have searched the records and have not been able to determine what consideration was given to fluid inertial effects at the time of the design of the experiments. Accordingly, we have reviewed the test and have calculated the relative magnitude of inertial effects in the loop as compared to the reactor. The analysis is shown in the attachment. It is based on using fluid kinetic energy as a measure of fluid inertia. The analysis is only approximate since it is not possible to precisely reflect all aspects of the flow reversal process. However the comparison indicates that the inertial effects were conservatively modeled in the tests in the sense that if the fluid kinetic energy in the test loop is greater than in the reactor fluid then the flow reversal process will occur more slowly in the test loop and is more likely to lead to overheating.

It is of interest to note that in 1966, a spurious indication on the liquid level system caused the reactor to go into flow reversal. At the time the reactor had been operating at 30 MW when a failure in the compressed air supply caused the depressurization valve to open, depressurizing the reactor. The helium makeup system which also provides helium for the liquid level instrumentation attempted to compensate for the pressure loss by adding helium at a high rate. As a result, the liquid level instrumentation sensed a spurious low liquid level indication which caused a trip of the low-low liquid level logic system. The main and shutdown pumps were shut down and flow reversal ensued. When the problem was diagnosed a few minutes later the shutdown pumps were restarted. There was no core damage as a result of this occurrence. The cause of the event was corrected by limiting the rate at which helium makeup can be added.

FLUID INERTIAL EFFECTS IN FLOW REVERSAL TEST LOOP COMPARED TO REACTOR

We calculate the fluid kinetic energy as a measure of the fluid inertial effects in the test loop and reactor vessel. In the test loop the elements in the recirculation path (Figure 2), starting at a point above the entrance box, is the entrance box, the heated test section, the 3 inch diameter section of pipe, a section of 2 inch diameter pipe and ball valve and an orifice. In the reactor vessel, (Figure 1) starting at a point above the transition plate, is the top inlet section of the fuel element, the fueled section of the fuel element, the bottom and side reflector region and the flow reversal valves. The total kinetic energy in each loop is the sum of the kinetic energy in each segment of the loop.

$$KE_T = \frac{1}{2g_c} \sum_i L_i A_i \rho_i V_i^2 \quad (1)$$

where

L_i = length of ith segment

A_i = flow area of ith segment

ρ_i = fluid density of ith segment

V_i = fluid velocity of ith segment

Let $G_i = V_i \rho_i$ and neglecting fluid density changes as a function of time

$$G_i A_i = G_j A_j = G_c A_c \quad (2)$$

where A_c is the total flow area of the fuel channels in the core or test section. G_c is the average mass velocity in core or test section channels.

$$KE_T = \frac{G_c^2 A_c^2}{2g_c} \sum_i \frac{L_i}{\rho_i A_i} \quad (3)$$

In order to compare the kinetic energies in the test loop and reactor, we first normalize by dividing the KE_T term by the channel area A_c

$$\frac{KE_T}{A_c} = \frac{G_c^2 A_c}{2 g_c} \sum_i \frac{L_i}{\rho_i A_i} \quad (4)$$

Next we account for the fact that the mass velocity is not the same in all channels in the core. The hot channel will go into boiling first and will have a higher mass velocity than the average channel in the process of establishing natural circulation. In the test section the average and hot channel G_c values are the same since the channels have identical heating rates. Thus

$$G_{HC} = F \times G_c \quad (5)$$

where F has a value greater than 1 in the core and equal to 1 in the test section. Combining expressions (4) and (5) we obtain

$$\frac{KE_T}{A_c} = \frac{G_{HC}^2 A_c}{2 g_c F^2} \sum_i \frac{L_i}{\rho_i A_i} \quad (6)$$

For equal values of G_{HC} in the core and test section and ignoring variations in fluid density, the expression $A_c/F^2 \sum L_i/A_i$ can be used to compare inertial effects in the 2 loops. This expression is evaluated in Table 1 for $F=1$ in the core and test section. It is seen that for this case the kinetic energy term for the 3 channel test section is approximately equal to the reactor vessel value while the result for the single channel test section is 74% of the reactor vessel value.

An accurate value of F for the reactor core during the transmit cannot be calculated. However, the relative flow rate values in the average and hot channel when natural circulation is established can be determined and used to provide an estimate of F . With a hot channel to average channel heating rate ratio of 2:1* a value of F of 1.3 is estimated. Incorporating this value of F in the expression for kinetic energy term, a value of 1.84 ft^{-1} is calculated for the reactor fluid. This brings the reactor value below both the single channel and 3 channel test values. This suggests that the test section results can be conservatively applied to the reactor in the sense that a higher kinetic energy system will go through the flow reversal process more slowly and is therefore more likely to experience overheating.

*Relative heating rates in hot and average channels in the core is determined from Ref. 1. Channel flow rates during natural circulation ~~is~~ obtained from Ref. 2.
 are

References:

1. P. Tichler, "Shutdown and Emergency Core Cooling Following Operation at 60 MW", dated April 5, 1978.
2. P. Tichler, "Safety of Flow Reversal Without Depressurization", dated March 3, 1978.

TABLE 1

Kinetic Energy Comparison

Region	A_i, ft^2	Reactor Vessel L_i, ft	$L_i/A_i, \text{ft}^{-1}$	$A_c L_i/A_i, \text{ft}$
fuel element top tube*	1.211	1.083	0.894	0.805
fuel Channels*	0.9	1.895	2.105	1.89
reflector**	31.6	4.5	0.142	0.128
flow reversal valves	9.8×10^{-2}	6.25×10^{-2}	0.318	0.286
			Sum =	3.11

*Values listed are for a full core of 28 elements

**Because of complex flow geometry, values listed are approximate. Uncertainty not significant because of small contribution made by reflector.

Test loop, 1 channel test section

Region	A_i	L_i	L_i/A_i	$A_c L_i/A_i$
top entrance box	1.475×10^{-2}	1.167	79.1	0.108
heated section	1.36×10^{-3}	1.833	1348	1.83
3" pipe section	4.91×10^{-2}	6.67	136	0.185
2" pipe section	2.18×10^{-2}	2.0	91.7	0.125
orifice plate	2.83×10^{-4}	1.04×10^{-2}	36	0.049
			Sum =	2.30

Test loop, 3 channel test section

Region	A_i	L_i	L_i/A_i	$A_c L_i/A_i$
Top entrance box	1.45×10^{-2}	1.167	79.1	0.323
heated section	4.08×10^{-3}	1.833	449	1.83
3" pipe section	4.91×10^{-2}	6.67	136	0.555
2" pipe section	2.18×10^{-2}	2.0	91.7	0.374
orifice plate	8.72×10^{-4}	1.04×10^{-2}	11.9	0.049
			Sum =	3.13

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