DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

BNL - 52497
UC - 406

RECEIVED
JUN 03 1996
OSTI

FLOW REVERSAL POWER LIMIT FOR THE HFBR

Lap Y. Cheng
and
Paul R. Tichler

October, 1995

Formal Report

Reactor Division

Brookhaven National Laboratory
Associated Universities, Inc.

Under Contract No. DE-AC02-76CH00016 with the
UNITED STATES DEPARTMENT OF ENERGY

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

BNL - 52497
UC - 406

FLOW REVERSAL POWER LIMIT
FOR THE HFBR

Lap Y. Cheng
and
Paul R. Tichler

October, 1995

DISCLAIMER

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ABSTRACT

The High Flux Beam Reactor (HFBR) undergoes a buoyancy-driven reversal of flow in the reactor core following certain postulated accidents. Uncertainties about the afterheat removal capability during the flow reversal has limited the reactor operating power to 30 MW. An experimental and analytical program to address these uncertainties is described in this report. The experiments were single channel flow reversal tests under a range of conditions. The analytical phase involved simulations of the tests to benchmark the physical models and development of a criterion for dryout. The criterion is then used in simulations of reactor accidents to determine a safe operating power level. It is concluded that the limit on the HFBR operating power with respect to the issue of flow reversal is in excess of 60 MW.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Dr. H.K. Fauske and Professor R.T. Lahey, Jr. for their suggestions during the planning of the flow reversal tests, and Professor P. Griffith for his review and comments on this report. The authors also have benefitted from helpful discussions with Dr. G.L. Yoder, Jr. who reviewed the report for the Reactor Safety Committee at Brookhaven National Laboratory.

The flow reversal tests were conducted at the Heat Transfer Facility of Columbia University and the authors gratefully acknowledge the effort of the staff there.

The authors thank Ms. Judith Spara for preparing this report and her patience in accommodating many revisions.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	iii
Acknowledgements	v
List of Figures	ix
List of Tables	x
I. Executive Summary	1
II. Test Program	5
A. Objective	5
B. Description	5
C. Test Results	8
III. RELAP5 Analysis of Tests and Development of Dryout Criterion	13
A. Comparison of Tests and RELAP5 Simulations	13
B. Channel Void Fraction as Dryout Criterion	13
IV. Simulation of Reactor Accidents	17
A. RELAP5 Model of Reactor	17
B. Analysis of Reactor Accidents	18
C. Sensitivity Study	20
V. Conclusion	23
A. Summary	23
B. Discussion	23
List of References	25
Tables 1 - 3	27 - 34
Figures 1 - 18	
Appendix A - Test Program	
Appendix B - RELAP5 Model and Comparison with Test Results	
Appendix C - Simulation of Reactor Accident with RELAP5	

LIST OF FIGURES

1. HFBR Vessel Showing Normal Flow Direction
2. Schematic of the Flow Reversal Test Loop
3. Schematic of Test Loop for First Test Series
4. Schematic of Test Loop for Helium Tests
5. Schematic of Test Loop for Extended Bypass Ratio Tests
6. Cross-Section of the Single-Heater Test Section
7. Stages of the Flow Reversal Process
8. Typical Trace of Time Averaged Channel Void Fraction
9. Channel Average Void Fraction Corresponding to Dryout Power Predicted By Various Correlations
10. Decay Power vs. Time After Shutdown
11. Cover Gas Pressure vs. Time After Accident Initiation
12. Primary Flow Rate vs. Time After Accident Initiation
13. Mass Flow Rate at Top of Heated Channels vs. Time
14. Mass Flow Rate at Bottom of Heated Channels vs. Time
15. Instantaneous Channel Void Fraction vs. Time
16. Time Averaged Channel Void Fraction vs. Time (Average Channel Group 2)
17. Time Averaged Channel Void Fraction vs. Time (Average Channel Group 6)
18. Time Averaged Channel Void Fraction at 2 Power Levels (Pump Trip Test Simulations)

LIST OF TABLES

- 1 Heated Section Dimensions
- 2.1 Summary of First Test Series Single Sided Heating
- 2.2 Summary of First Test Series Two Sided Heating
- 2.3 Summary of Helium Effects Tests
- 2.4 Summary of Extended Bypass Ratio Tests
- 3 List of RELAP5 Simulations of Flow Reversal Tests

I. EXECUTIVE SUMMARY

The HFBR at Brookhaven National Laboratory (BNL) is a research reactor which is fueled by 93% enriched uranium and is cooled, moderated, and reflected by heavy water. The core is composed of 28 fuel elements with each element made up of 18 fuel plates in a parallel plate array. The aluminum clad fuel plates are 0.05 inch thick and are spaced to provide coolant channels about 0.1 inch thick and 2.5 inch in width. During normal operation the coolant flow direction, as indicated in Figure 1, is downward through the core. For emergency shutdown heat removal, the HFBR employs a scheme that provides a return path around the core so that natural circulation cooling can be established. The return path is provided by the opening of four spring-loaded flow reversal valves. These valves are held closed during normal operation by the head developed across any one of the two primary and shutdown coolant pumps. If all pumping power is cut off, either by loss of electrical pumping power or because of automatic safety action, flow coastdown will begin. The flow reversal valves open automatically when the head developed by the pumps can no longer maintain the valve springs in tension. When the downward core flow reaches a value at which the thermal buoyancy head is comparable to the friction losses in the core, flow reversal occurs.

At the time that the reactor was being designed (1960) there were data [1] that indicated that while the decay heat removal capacity with natural circulation was more than adequate, there were little data on the flow reversal transient itself. Accordingly a series of tests [2] were undertaken at that time to establish the limiting shutdown heating rate. These tests were simple, go, no-go tests in which the success criterion was the absence of rapid temperature excursions in the test section. In 1982 after a number of plant modifications were made the reactor power was increased from 40 to 60 MW. During the period 1989-1991 reviews by the Department of Energy (DOE) raised the issue of the prototypicality and the applicability of these earlier tests to 60 MW operation of the HFBR. At that time, critical heat flux data and correlations were available for steady-state upflow and downflow in channel geometries and conditions similar to the HFBR [3,4]. However, because of the transient nature of the flow reversal process it was not apparent how these steady-state correlations should be used. Therefore, a more conservative heat removal limit was formulated for the HFBR based on the flooding limit and the nominal operating power level was reduced to 30 MW.

In an effort to provide a more realistic and defensible estimate of the flow reversal heat removal limit and thereby increase the HFBR power level, a series of flow reversal tests were conducted for BNL at the Heat Transfer Research Facility (HTRF) of Columbia University. In conjunction with these tests, models of the test loop and the HFBR were developed using the thermal

hydraulics code, RELAP5. The purpose of this modeling effort was to benchmark the code against the test results and then use the HFBR model to analyze loss of flow accidents and to determine the power limit.

As a result of these analyses and experiments an empirical dryout parameter, based on the calculated void fraction in a channel during flow reversal, has been developed. The use of channel void fraction was suggested by Griffith et.al. [5] in a correlation for low mass flow data which relates critical heat flux (CHF) to void fraction. In addition, it was observed in the flow reversal tests that a thermal excursion occurred in the heated section when a high void fraction existed in the channel for a short but finite period of time. This period of high void fraction that existed prior to the excursion suggests that the excursion was caused by liquid film dryout. Further evidence that dryout rather than departure from nucleate boiling (DNB) is the thermal excursion mechanism and that global rather than local conditions are important is provided by a comparison of the one-sided heating tests with the two-sided heating tests. The channel power at which the excursion occurred in the two sided heating tests were only a few percent higher than in the one sided tests while the heat flux in the one sided tests were about twice as high. While dryout power is usually correlated with the boiling length in a channel [6], boiling length is not a well defined quantity in the flow reversal transient. These considerations led to the following form of the dryout parameter. The channel void fraction during flow reversal was calculated and the results were time smoothed to obtain a 2 second running average of the void fraction. The maximum value of the time smoothed void fraction during the transient is the measure of whether dryout will occur. A limiting value of this parameter has been established which conservatively bounds dryout for the wide range of conditions examined in the Columbia tests. The void fraction criterion has also been tested against steady state CHF correlations developed elsewhere for conditions similar to the HFBR [7]. In these comparisons RELAP5 was used to compute a steady state channel void fraction at the power predicted by the correlations for a range of mass flow rates. The computed steady state void fractions fell within the range of the 2 second void fractions determined from the Columbia test simulations.

In applying the void fraction criterion to the RELAP5 analysis of loss of flow accidents in the HFBR, it is concluded that flow reversal can occur without fuel damage at afterheat rates corresponding to reactor power levels in excess of a nominal 60 MW with a margin of at least a factor of two. Similar conclusions can be drawn by examining the test data directly, independent of the RELAP5 analyses. Successful flow reversal occurred in the Columbia tests at power levels that are greater than the decay power in the hottest HFBR channel at the time of flow reversal following 60 MW operation. The margin to thermal excursion depends on a judgement

as to which test most closely matches the conditions in the multi-channel HFBR core. The margin is about 15% if it assumed that the heating rates in all the channels in the core were the same and equal to the hot channel heating and all channels reversed simultaneously. If credit is taken for the beneficial effect of multiple lower powered channels and the rapid decay of primary flow during flow reversal, the margin is 2.4. The margins conservatively account for analytical and other uncertainties.

THIS PAGE IS BLANK

II. TEST PROGRAM

A. Objective

This section discusses the important aspects of the tests including the objectives, test description and results. More detailed information is given in Appendix A.

The program was designed to capture, as closely as possible, the essential features of the flow reversal transient in the reactor.

1. Scaling to achieve similar thermal-hydraulic responses.
2. Spatial variation of heat generation.
3. Rate of flow coastdown on loss of pumping power.
4. Effect of flow impedance of flow reversal valves.
5. Effect of liquid level.
6. Effect of pressure.
7. Effect of initial water temperature.
8. Effect of helium evolution on depressurization.

Another objective of the test program, separate from the issue of prototypicality, was to provide a means of visualizing the flow reversal process. This was accomplished in one series of tests by designing the test channel with one side heated and one side transparent. Recordings were taken with a video camera.

B. Description

The tests were performed with an electrically heated single channel section representing the core, an orifice representing the flow reversal valves, a variable speed pump to simulate the flow coastdown, and auxiliary piping and equipment to simulate other pertinent structures in the reactor vessel. The test loop was set up to preserve the vertical height of the natural circulation flow path in the HFBR vessel. The heated section was a full-size mockup of a typical channel in a HFBR fuel element. The flow areas of the test loop were scaled to correspond to a typical coolant channel in the HFBR. The top of the upper plenum region was open to the atmosphere. Demineralized water was the working fluid of the test loop.

Figure 2 is a drawing of the test loop used for the first series of tests showing component dimensions. The loop was modified to extend the range of variables investigated. However,

the overall dimension of the loop was unchanged. Figures 3 through 5 are schematics of the various test loop configurations used.

The fuel plates were simulated in the test by 6061 aluminum plates of similar thickness and powered by direct DC heating. Two separate heater arrangements were used in the experiments. The single-sided arrangement had one heater plate and a transparent Plexiglas separated by the coolant gap. The double-sided heater had a heater plate on each side of the coolant gap. The cross-sectional view of the single-sided heater is shown in Figure 6. The channel gap was maintained by two spacer rails installed along the side edges of the channel, overlapping the heater plate(s) by ~0.05 inch. The dimensions of the two heated sections are shown in Table 1.

The heated section was powered by a set of direct current generators rated at 250 volts. The low electrical resistance of aluminum resulted in a voltage drop of only ~2 volts across the length of the heater plates. At low voltages the generator output was prone to drift. A ballast was installed in series with the heater plates(s) to raise the total resistance seen by the generator and stabilize the output voltage.

The initial flow through the heated section and the bypass orifice was provided by an eccentric screw pump which has the characteristics of a positive displacement pump. The effect of flow coastdown was created by using a programmable speed controller to vary the rotational speed of the pump motor.

The test loop was instrumented to continuously record water temperatures, heated plate temperatures, flow rates and power (voltage and current) to the heated plate. The instrumentation layout for the various test configurations are shown in Figures 3 to 5.

The plates were protected from overheating during the experiments by two types of power trips - on plate temperature rise and on increase in voltage across the plate. A voltage increase would occur when the plate temperature increased because of the increased plate resistance with temperature. The trip settings on temperature and voltage rise were conservatively set so that the heated plate was not damaged and could be reused in subsequent tests.

A number of parameters were varied in the tests to examine their effects on the thermal limit. In the first series of tests these parameters were rate of flow coastdown, inlet subcooling, water level in the upper plenum, single sided vs. two sided heating and bypass ratio (ratio of initial flow through the heated section to initial flow through the bypass path). This ratio is a measure of the flow impedance in flow path which simulates the flow reversal valves in the reactor. A schematic of the test loop for

the first test series is shown in Figure 3.

In the second series of tests the loop was modified to permit simulation of the evolution of helium. In the reactor, helium gas is evolved from solution when the reactor which is normally pressurized with helium to 200 psig, is depressurized. Depressurization occurs in accidents involving loss of coolant. The maximum anticipated void fraction is 15%. Since the test loop was not designed for 200 psig, the helium void effect was achieved in the tests by saturating a volume of water with helium in a separate pressurized tank and injecting the depressurized solution into the test loop. A range of bypass ratios were also examined in this test series. The schematic of the test loop for this test series is shown in Figure 4.

In the last series of tests the test loop was modified to expand the range of one of the parameters investigated, the bypass ratio (see Figure 5). This was done to test the RELAP5 model against a broader data base and to provide a way to simulate the effects of multiple parallel channels in a single channel test. Since all the channels in the core are not heated equally and therefore do not reverse simultaneously, the cooler channels which are in downflow provide a secondary return path in parallel with the flow reversal valve path. The parallel channel simulation is achieved by reducing the flow impedance of this path relative to the test channel which in turn reduced the bypass ratio from a nominal 2:1 to 1:3.4. Another effect related to the presence of multiple parallel channels in the core was examined in this test. While the core is in downflow, the water temperature in the plenum region below the core will represent the average temperature of all the channels rather than the hottest channels. When reversal occurs in a channel the water temperatures entering this channel will be this average temperature. In a single channel test this effect is simulated by injecting unheated water into the region below the test section so that it mixed with the hot water exiting the test section.

As seen in Figure 5, the schematic for the last series of tests, a turbine flowmeter that was in series with the test section in the earlier tests was eliminated and replaced with a magnetic flow meter. This was done to reduce the pressure drop in this flow path. It turned out that the pressure loss in the turbine flow meter (0.3 psi at 2 gpm) was substantial in comparison with the test channel pressure drop (≈ 0.15 psi). This was overlooked and was not recognized until after the first 2 test series were completed and the last test series began. The pressure loss in the magnetic flow meter is relatively low (≈ 0.03 psi) and is comparable to the pressure loss in the reflector region of the reactor.

In each test, steady forced flow conditions were established at a fixed power and a flow rate corresponding to a time in the reactor loss of flow accident where the primary flow rate has fallen to about 7% of its operating value. The test was then initiated by linearly reducing the pump flow to simulate the final coastdown of the reactor pumps to zero flow. The test was considered to be a successful flow reversal, if natural circulation cooling was sustained without a trip of the power for 30 seconds. For a given set of test conditions, the flow reversal experiment was repeated at increasing power levels until the thermal limit was bracketed within about 0.5 kW.

C. Test Results

Based on observation of the flow reversal tests, the reversal process can be divided into four stages. The progression of a flow reversal transient is depicted in Figure 7. The four stages of a flow reversal transient are:

1. Coastdown Stage

As the flow is coasting down in the heated channel, the coolant temperature gradually increases to the point when steam voids begin to appear in the channel.

2. Vapor Generation Stage

The steam voids continue to grow and start to move in an upward direction. Soon a vapor slug occupies the whole heated section.

3. Oscillatory Flow Stage

This is a transitional stage before a more stable natural circulation flow is established. This stage is characterized by a cyclic behavior in which steam voids are first generated followed by reflood from the bottom. The expulsion of coolant due to steam generation and the refilling of the coolant channel by bottom reflood are visible through the oscillation of the boiling boundary in the heated section. The upper portion of the channel is in the churn-turbulent flow regime. The sequence of expulsion and reflood generally lasts for a few cycles.

4. Natural Circulation Flow Stage

Natural circulation flow is established in the heated section and there is no overheating of the channel walls.

In the tests, all safe flow reversal cases eventually went through the four stages described above. For those cases which ended in a power trip the rapid generation of steam in the heated

section impeded the return of the liquid during the oscillatory flow stage. In successive reflood cycles less and less liquid entered the heated section. A power trip occurred as a substantial portion of the channel stayed in a voided state for more than a couple of seconds. In a couple of cases that were conducted at higher powers, a power trip occurred before the flow reversal.

Detailed results of all the tests conducted are presented in the reports by Columbia University [8]. These reports include a tabulation of lower power tests in addition to the threshold power for a given set of test conditions. The Columbia tabulation has been consolidated for presentation here by eliminating the lower power tests and only including two test results for each set of conditions. One is the highest power level at which successful flow reversal occurred and the other is the power level at which a trip of the power occurred.

The results for the first series of tests is shown in Tables 2.1 and 2.2. The helium evolution tests results are shown in Table 2.3 and the final test series with the reduced bypass ratios are shown in Table 2.4. Note that while the first test series used both single sided and two sided heating arrangements, the remaining tests were all performed with a single sided heater.

Depending on the test conditions the threshold power (highest power for successful flow reversal) varied from 7 to 19 kW. The threshold power corresponding to the base case conditions (130°F inlet temperature, 40 second coastdown time, 2:1 bypass ratio, 14 ft water level) is 9 kW. This value is obtained from the first test listed in Table 2.4 (with a 4% heat loss correction). 9 kW is about 2 kW higher than the threshold power obtained for the base case condition in the first 2 series of tests. As explained earlier, the test loops in the first 2 series of tests contained a turbine flow meter in series with the test section which had a high pressure drop. This flow impedance was eliminated in the last loop modification which closely matches the reactor flow impedance.

Several conclusions can be drawn from the test results.

1. The power limit increases with decreasing coolant inlet temperature.
2. The power limit increases with shorter coastdown time. The increase in the power limit from the base case coastdown time of 40 seconds to the pump trip case (≈ 1.5 seconds) was about 50%.
3. The power limit increases with an decrease in flow impedance of bypass paths. The power limit increased about 50% when the bypass ratio was changed from the base case value of 2:1 to 1:3.4.

4. The highest threshold power (19 kW) occurred in the pump trip case with low impedance in the return path. This power is about three times the power in the hottest core channel during potential accidents. The true threshold power was not reached for these test conditions. When the power was raised to 21 kW the power trip occurred while the power was being increased and before the pump was shutoff.
5. Two-sided heating results in a slightly higher power limit than one-sided heating.
6. The height of water in the upper plenum has a negligible effect on the power limit.
7. The reduction in the power limit due to helium voids will not exceed 10%.
8. The results are reproducible.

There are qualitative explanations for these results. Flow reversal is generally initiated prior to the end of the coastdown of the pump. With the flow still present in the bypass path, the pressure drop across the bypass resistance acts in opposition to the thermal buoyancy which is driving the reversal. If this opposing force is large enough and lasts long enough dryout will occur. Thus a shorter coastdown time and a smaller impedance in the bypass path will increase the dryout power. The highest dryout power measured in the tests was for the case of a pump trip with low impedance in the bypass path. For the pump trip tests the coastdown time is short (≈ 1.5 seconds) so that the flow impedance which is already small disappears quickly.

A lower water temperature at the inlet to the channel will delay the onset of flow reversal so that reversal occurs later in the coastdown period. The pump flow and bypass flow rates are lower at this time and therefore the flow resistance in the bypass path is lower.

The two sided heating vs. one-sided heating results indicate that the thermodynamic condition of the fluid as determined by the power input is much more important than local heat flux in determining dryout.

The difference in liquid level would be expected to affect the dryout power because of the difference in saturation temperature and vapor density. The static pressure in the channel at the two liquid levels are 18.7 and 23.2 psia. Evidently the differences in saturation properties are not large enough to be distinguished by the tests which can only bracket the dryout power within 5-10%.

The presence of helium voids would be expected to affect the flow reversal process through its effect on hydraulics (flow is two

phase before boiling begins) and because it adds to the voids produced by steam. However the void fraction due to helium is only 15% and the relatively high rate of steam generated will rapidly displace the helium in the heated channel.

THIS PAGE IS BLANK

III. RELAP5 ANALYSIS OF TESTS AND DEVELOPMENT OF DRYOUT CRITERION

More detailed information about the code and the test comparisons is given in Appendix B.

A. Comparison of Tests and RELAP5 Simulations

RELAP5 is a system thermal-hydraulics code developed at the Idaho National Engineering Laboratory (INEL) for the analysis of power reactors. Recent updates to RELAP5 has made the code more applicable to DOE research reactors. The version of RELAP5 used in the simulation of the flow reversal tests is mod 3.1.1.1 released to BNL by INEL in July 1994. During the development of the RELAP5 model for the flow reversal tests, it was observed that high steam condensation rates were calculated at the steam-water interface resulting in unrealistic simulation of the tests. The interfacial heat transfer coefficient on the liquid side was modified to reflect the conditions observed during the actual tests. In effect, the coefficients are reduced for the bubbly subcooled liquid and the slug subcooled liquid flow regimes.

RELAP5 simulations of selected tests were generated for detailed comparison with the test data. In summary, the RELAP5 simulations of the flow reversal tests are found to reproduce the general aspects of the observed behavior of the tests. These include the timing of the onset of flow reversal, the period of flow and void oscillations, and the extensive voiding that was observed visually prior to dryout. However, the calculated plate temperatures tended to be higher than the measured values. The heat transfer correlations in RELAP5 are based primarily on data developed for rod bundle and tube geometries and high pressure conditions applicable to power reactors. The accuracy of applying the existing heat transfer correlations to narrow channel geometry and low pressure conditions has not been established. In the following section an alternative dryout criterion is developed which is based on the use of channel void fraction .

B. Channel Void Fraction as Dryout Criterion

Channel void fraction as a criterion for dryout was prompted by a correlation developed by Griffith, et.al. [5] for low mass flow data (upflow, counterflow, downflow) which relates critical heat flux (CHF) to void fraction. Visual observation of the one-sided heating tests and channel pressure drop data indicated that temperature excursion occurred in the heated section when a high void fraction existed for short period of time. This high void fraction interval prior to the temperature excursion suggests that liquid film dryout was the cause of the excursion. This conclusion is consistent with the results of the two sided heating tests in comparison with the one sided heating tests. The power at which the temperature excursion occurred in the one-sided heating tests was only a few percent higher than in the two-sided tests while the

heat flux in the one-sided tests were about twice that of the two-sided tests.

The form of the dryout criterion was developed empirically. It was recognized that a high void fraction would have to be sustained for some period to cause a temperature excursion. The instantaneous peak void fraction calculated by RELAP5 was in excess of 90% for all tests and was not a useful discriminator for dryout. Instead the void fraction was time smoothed to obtain a two second running average of the channel void fraction. Two seconds is the approximate time between successive voiding and reflood cycles observed visually in the tests and in the RELAP5 calculations. Typically after the first couple of cycles the observed and calculated voiding decreased in magnitude. Sensitivity studies were done to determine if a shorter (1 second) or longer (3 second) smoothing time resulted in a more reliable criterion. Although there were not large differences, a 2 second smoothing time was judged to be the best.

The two second time averaged channel void fraction is calculated as a function of time for the flow coastdown and reversal transient. The peak value of this parameter in the interval following reversal is the criterion for determining whether dryout will occur. A typical trace of the time averaged void fraction is shown in Figure 8, which is based on a simulation of one of the test runs. It is seen that the maximum time averaged void fraction is 0.7 shortly after reversal and then decreases as natural circulation is established.

Time averaging was performed on the RELAP5 simulation of tests that are identified in Table 3. The maximum time averaged void fraction for each of the test simulations is shown in this table. These tests cover a wide range of inlet temperatures, bypass ratios, and coastdown times and include both one sided and two sided heating tests. As expected, the value for no dryout is lower than the dryout value for each test condition. For purposes of establishing a conservative criterion for the dryout threshold, only the no dryout data are used. The sample mean and standard deviation for the 17 points were calculated as $\bar{x} = 0.75$ and $s = 0.083$. The no dryout threshold values range from 0.55 to 0.89. A 95/95% one-sided confidence limit of 0.54 is calculated.

Note that for three of the test conditions, a RELAP5 simulation was done only for the no dryout case. In tests identified as B081395L, M and O in Table 2.4, the power was tripped before the flow had reversed. This was observed and confirmed by the experimental data. The highest plate temperature was at the bottom of the plate rather than the top as was the case in the other tests where dryout occurred after reversal. In the pump trip case, B081795D a power trip occurred while the power was being raised and before the pump was shutoff. It was not considered appropriate to apply the void fraction analysis to these four

cases.

As a further test of the generality of this criterion for predicting dryout under conditions appropriate to the HFBR, CHF correlations based on data obtained at other laboratories were used. These correlations were generated from data obtained under low flow and low pressure conditions for narrow channel geometries similar to the HFBR. These were steady state tests in which CHF was measured as a function of mass velocity and inlet subcooling. A RELAP5 model of a typical HFBR channel was used to compute channel void fraction for a selection of mass velocities and a typical subcooling [7]. The results are shown in Figure 9. The differences in void fractions calculated for a given mass flux reflect the different dryout power predicted by the correlations. However they all fall in the range of 0.77 to 0.89 which is within the range of the two second void fractions calculated for the Columbia data.

THIS PAGE IS BLANK

IV. SIMULATIONS OF REACTOR ACCIDENTS

More detailed information on reactor accident simulations is given in Appendix C.

A. RELAP5 Model of Reactor

In the core region, the 532 channels are divided into two channel types, hot and average. The model has 3 hot channel groups representing the different channel dimensions (Numbers 2, 3 and 4 in the fuel element). There is more than one potentially hot channel because of the possibility that a narrower channel with a slightly lower heating rate will be more limiting than a wider channel with a higher heating rate. The average channel type contains geometrically identical average channels. This type is divided into 7 groups, each with a different heating rate. Within these 7 groups, group No. 7 has the highest heating per channel and group No. 1 has the lowest. Each of the 3 hot channel groups contain 14 channels and each of the 7 average channel groups contain 70 channels.

Fission and decay heat are modeled as a volumetric source uniformly distributed in the fuel cermet. Cladding is included in the model. In the base case calculation there is no axial or spanwise variation. The effect of axial variations are examined in a separate calculation. The time dependence of power density following shutdown is modeled. The time dependence for the highest powered channel is shown in Figure 10 [9]. The shape of the power vs. time curve is similar for other channel groups.

The base case power at a nominal 60 MW is increased in the RELAP5 calculation to 64.05 MW to account for operational variations in reactor power (± 1 MW) and power measurement uncertainty (5%). An additional factor of 1.23 is applied to the decay power to account for the uncertainty in the calculation of decay power and the helium evolution effect (10%) which could not be explicitly included in the model. The 10% helium evolution effect is based on the tests which showed that the effect will reduce the power by no more than 10%.

The other important structures in the primary system were explicitly modeled. However where equivalent structures were in parallel such as the 2 parallel loops and the 4 flow reversal valves, they were lumped into one equivalent structure. In the case of the flow reversal valves an additional calculation was done with one of the 4 valves in a failed state. The shutdown pumps and pony motors were assumed not to operate.

Plant data were used to benchmark the primary pump model and the depressurization of the reactor via the valve HCe-102. Sensitivity studies were done to examine the effect of different pump coastdowns. Trip setting used were obtained from the 60 MW

accident analysis.

B. Analysis of Reactor Accidents

There are two types of potential accident scenarios which could lead to loss of forced flow cooling and flow reversal. One is a loss of cover gas pressure with the shutdown and pony motors not available. The other type is a LOCA event which results in the liquid level dropping below the 197 inch level at which pump trip occurs. In these accidents a reactor trip occurs first and is followed by a trip of the primary pumps. The time interval between these 2 events determines the decay power at the time flow reversal occurs. The shorter is this interval, the higher is the decay power. The accident scenario which has the shortest interval between reactor trip and pump trip is a cover gas depressurization in which the depressurization is caused by a breach in the cover gas system. The breach size is a circular opening 1.39 in² in area and is based on the design basis break in the 60 MW FSAR. In this accident, both reactor and pump trips occur within 2 seconds of accident initiation and the reactor is completely depressurized in 14 seconds.

Several variations of the cover gas depressurization accident were performed using RELAP5 to determine the effect of changes in some of the input parameters. The base case will be discussed in some detail first and the results of the other cases will then be summarized. More detailed results are given in Appendix C.

The initial power for the base case was 64.05 MW and that corresponded to a nominal reactor power of 60 MW. Both the reactor trip and the primary pump trip were activated by the low pressure trip setpoints for the cover gas. Figure 11 shows the rapid depressurization of the cover gas following the break initiation at time zero.

The primary pump coastdown began in less than one second after the reactor trip. Figure 12 shows the primary flow rate of the primary pump as a function of time.

The junction mass flow rates at the top and bottom of the heated section of the three hot channel groups are shown in Figures 13 and 14 respectively. In these figures the positive flow direction was downward. It is seen that flow reversal occurs in each channel periodically for the duration of the calculation (≈ 100 sec.). The first flow reversal in the three hot channel groups occurred at about the same time (≈ 47 sec. after reactor trip). Among the three hot channel groups, the first to go through flow reversal was group number 3 which had the lowest power of the hot channels but the narrowest channel gap (0.095 inches).

The periodic flow behavior also occurs in the seven average channel groups except that the magnitude of the flow fluctuations is smaller than for the hot channel groups and the first flow reversal occurs later.

The state of the coolant in the channel is characterized by the channel void fraction which is shown for several channel groups in Figure 15. The periodic behavior of the channel void fraction can be characterized by two stages, a boiling stage and a heat up stage. When the coolant reached the boiling condition, the generation of steam voids in a channel resulted in a rapid increase in the channel void fraction. Flow began to enter the channel because of the density difference between the coolant channel and the reflector region. The coolant quickly condensed or displaced the steam in the channel and cooled down the heated wall. When the channel was occupied by single-phase liquid, the mass flow was reduced and the coolant in the channel began to heat up to boiling again. The flow in the heated channel was seen to alternate between two-phase and single-phase conditions.

The 2 second time averaged channel void fraction as a function of time is shown in Figures 16 and 17 for a hot and average channel group. The channel groups selected contain the highest value of the 2 second void fraction. The maximum value is 0.28 for the hot channel group and 0.31 for the average channel group. These figures are typical of all the groups except for the lowest powered of the average groups, group Nos. 1 and 2. In these the time averaged void fractions are less than 0.02.

In the case of the HFBR with variable heating rates in the channels, flow reversal does not occur simultaneously in all channels. With some of the channels in upflow while others in downflow, the coolant from the downflow channels becomes an extra source for feeding the upflow channels. This extra source supplements the core bypass flow and the flow through the flow reversal valves. The existence of downflow channels is similar in effect to an increase in the bypass orifice used in the single-channel flow reversal test. The apparent increase in the bypass flow area in the HFBR is the principal cause of a lower channel void fraction calculated for the reactor as compared to the single-channel test.

Another aspect of the flow reversal in the reactor is the effect flow reversal has on the rate at which the flow rate in the primary system decays. The thermal buoyancy generated in the core as the coolant temperature rises and as channels begin to reverse acts as an increased flow resistance and will cause the flow generated by the centrifugal pump, as it coastsdown, to fall more rapidly than it otherwise would. Thus a single channel test with a rapid flow coastsdown is more representative of reactor conditions.

It is of interest to compare the relatively low channel void fraction calculated for the multichannel reactor (0.31) with the single channel test simulations with the object of determining what single channel test conditions most closely approximated the multichannel reactor core. Previous discussions suggest that a single channel test with a rapid coastdown and a large bypass can be considered a good representation of flow reversal in a multichannel core. The test that most closely approximates these conditions is Test No. B081795C in Table 3. It has a bypass ratio of 1:3.4:0.6, a short coastdown time (≈ 2 sec) and a power of 19 kW. The two second void fraction calculated by RELAP5 is shown in Figure 18. Also shown in this figure is the RELAP5 calculation of the two second void fraction under the assumption that the test conditions were the same but the channel power was 7.8 kW instead of 19 kW. Note that a test at this low power was not actually conducted under these conditions. The lowest power in this test series was 14 kW. In any event it is seen from Figure 18 that the maximum two second void fraction for the 7.8 kW case is 0.32 which is almost identical to the two second void fraction computed for the identically powered hot channel in the reactor. This comparison supports the applicability of the previously discussed single channel test conditions to the reactor.

In order to provide added confidence in the ability of the RELAP5 code to predict flow reversal in a multi-channel configuration another simpler numerical model based on the drift-flux formula was developed [10]. Both codes were used to simulate flow reversal in a test case which consisted of 4 parallel channels with different heating rates. The codes predicted similar flow behavior and fairly good agreement in the timing of flow reversal was obtained.

C. Sensitivity Study

Details of the sensitivity study, including the many figures generated are given in Appendix C.

1. Non-uniform axial power distribution

The power density variations that exist within each plate were not accounted for in the base case calculation. The axial power density shape is a function of time in the operating cycle and varies from plate to plate at a given cycle time. To address this issue an axial flux shape which was close to the shape in a peripheral fuel element in a freshly fueled core was selected. All the plates in the core had the same normalized shape. In this shape the peak power density occurs at the midplane and the power density is lower at the top and bottom. In a second case the shape was inverted so that the maximum power density occurred at the top and bottom and the midplane has the lowest value.

There are differences in the channel void fraction between the cases of uniform and non-uniform axial power distribution. However, in all the channel groups regardless of the axial power shape, the maximum time-averaged channel void fraction is in the range of 0.25 and 0.31. The maximum time averaged channel void fraction is thus not sensitive to the axial power shape in the core. Hence it is justifiable to use a uniform axial power distribution in RELAP5 calculations to determine the maximum time-averaged channel void fraction.

2. Effect of Doubling Reactor Power

The base case calculation indicates that flow reversal will be successful in the HFBR because the maximum time-averaged channel void fraction for the coolant channels is below the critical void fraction of 0.54. In order to establish the margin to dryout during flow reversal, the channel power needs to be increased to a level such that the maximum time-averaged channel void fraction approaches the critical void fraction. Another RELAP5 calculation was done with the reactor power and the decay power increased by a factor of two over the base case value. A comparison with the result of the base case shows that, for the case of a higher channel power, the time to flow reversal from pump trip is shortened and the maximum time-averaged channel void fraction is increased to 0.5. For this higher power case, the initial reactor power is 128.1 MW and the multiplier applied to the decay power is 1.2276 (1.116 x 1.1). Including the multiplier, the decay power used in the calculation is equivalent to a reactor power of 157.26 MW. Even at this elevated power, the maximum time-averaged channel void fraction is still less than the critical void fraction.

3. Effect of One Closed Flow Reversal Valve

A variation of the accident scenario is the failure of one of the four flow reversal valves to open. With one valve remaining closed, there is a reduction in the area available to the coolant flow that bypasses the core. The previous RELAP5 calculation was redone with one flow reversal valve closed. As compared to the previous case, the time of flow reversal is delayed slightly. This is because of a slight increase in the channel flow when the effective bypass flow area is reduced. The maximum time-averaged channel void fraction during flow reversal is slightly lower for this case (0.47 verses 0.50). Thus the failure of one of the flow reversal valves to open has negligible effect on the maximum time-averaged void fraction.

4. Effect of variations in the pump coastdown

These simulations were accomplished by adjusting the pump torque coefficient in the RELAP5 model. Two cases were done,

one in which the coefficient was increased by a factor of 1.5 and another in which it was reduced by a factor of 1.5. The power level was a nominal 120 MW. While there are differences in the timing of flow reversal in the channels the maximum 2 second channel average void fraction is unchanged at 0.5.

V. CONCLUSION

A. Summary

It is concluded that if flow reversal were to occur due to a loss of coolant accident while operating at 60 MW (nominal), the transient would occur without fuel damage. The margin to the onset of fuel damage is substantial and can be calculated in a number of ways. Numerical values for these margins presented as "safety factors" are listed below. These factors should be interpreted as a number by which the 60 MW decay heat needs to be multiplied to reach the fuel damage threshold. It should be recognized that, for reasons unrelated to the flow reversal issue, the HFBR is not designed to operate above 60 MW. The safety factor conservatively accounts for analytical uncertainties; i.e. the factor would be larger if the uncertainties were ignored.

1. Based on application of 2 second time averaged void fraction: >2.0 .
2. Based on test results only: 1.15-2.4 (see discussion below).

B. Discussion

The following uncertainties are included in the safety factor estimate.

1. Operational variations in reactor power: (± 1 MW) 1.67%
2. Reactor power measurement: 5%
3. Decay power calculation: 11.6%
4. Helium void fraction effect: 10%

The uncertainty in the measurement of the power to the test section is insignificant (0.5%). Other uncertainties in the test have been conservatively accounted for in the RELAP5 modeling. The four uncertainties listed above are combined multiplicatively rather than statistically. The combined factor due to uncertainties is therefore 1.31.

The safety factor of >2.0 based on the analysis for the reactor accident and applying the two second channel void fraction criterion was calculated as follows.

A RELAP5 simulation of a reactor accident with an initial power of 157.26 MW (Section IV.C.2) resulted in a maximum two second channel void fraction of 0.5. A higher reactor power would be required to reach the 0.54 critical void fraction value. The safety factor is therefore greater than $157.26 / (60 \times 1.31) = 2.0$.

The safety factor developed from the test data independent of the void fraction criterion depends on a judgement as to the appropriate test result to compare with reactor conditions. A conservative factor is obtained by using the test results for base case conditions (130°F inlet temperature, 2:1 bypass ratio, 40 second coastdown time). The power limit for this case is 9.0 kW (Table 3, Reference test no. B081395E). This is compared with the decay power input to the hottest channel in the core at the time of reversal (47 seconds). The decay power, 7.8 kW, includes all the uncertainties listed above. The safety factor for this case is calculated as $9.0/7.8 = 1.15$. Note that this represents an unrealistically low value since it would apply to a reactor in which all the channels in the core had a heating rate equal to the hottest channel and all the channels reversed simultaneously.

A safety factor which is considered to be more realistic can be obtained by using a test result which is based on conditions more representative of the multi-channel core. Since the heating rates in the core channels vary, flow reversal will not occur in all channels at the same time. As explained in Section IVB, the hottest channels, which reverse first, are supplied with coolant not only from the flow reversal valves but also from channels still in downflow. A second effect that needs to be considered is that the primary pump flow rate will fall very rapidly at the time of flow reversal (Figure 12). The rapid flow reduction is caused by the increased buoyancy head that the centrifugal pump "sees" as the water in the core heats up. The test with a 40 second coastdown and a positive displacement pump will not represent this condition. Thus the test condition that most closely approximates reactor conditions is the test with a small bypass ratio and a rapid flow coastdown (Table 3, Reference test no. B081795C). The thermal limit for this case is 19 kW and the safety factor is 2.43 ($19/7.8$).

References:

- [1] Gambill, W.R. and Bundy, R.D., 1960, "Burnout Heat Fluxes for Low-Pressure Water in Natural Circulation," ORNL-3026.
- [2] Tichler, P.R., and Hill, F.B., 1963, "Experimental Evaluation of the HFBR Emergency Cooling System," BNL-12476 (issued in May 1968).
- [3] Mishima, K. and Nishihara, H., 1982, "The Effect of Flow Direction and Magnitude on CHF for Low Pressure Water in Thin Rectangular Channels," Nuclear Engineering and Design, 86, pp 165-181.
- [4] Sudo, Y., et.al., 1985, "Experimental Study of Differences in DNB Heat Flux between Upflow and Downflow in Vertical Rectangular Channels," J. Nuclear Science and Technology, 22, pp 604-618.
- [5] Griffith, P., Avedisian, C.T. and Walkush, J.P., 1975, "Counterflow Critical Heat Flux," 15th National Heat Transfer Conference, pp. 149-155.
- [6] Lahey, R.T., and Moody, F.J., 1993, "The Thermal-Hydraulics of a Boiling Water Nuclear Reactor," 2nd edition, American Nuclear Society.
- [7] Cheng, L.Y., October 1995, "Steady-State Channel Void Fraction Calculated by RELAP5," BNL Memorandum.
- [8A] Yang, B.Y., et.al., 1993, "Brookhaven National Laboratory Single Channel Test Program for the HFBR," Columbia University Heat Transfer Research Facility, CU-HTRF-93-05 (Final Report, Vols. I and II).
- [8B] Yang, B.Y., et.al., 1994, "Brookhaven National Laboratory Single Channel Test Program for the HFBR - Helium Evolution and Bypass Flow Restriction Effects," Columbia University Heat Transfer Research Facility, CU-HTRF-94-02 (Final Report Vols. I and II).
- [8C] Yang, B.Y., et.al., 1995, "Brookhaven National Laboratory Single Channel Test Program for the HFBR - Flow Reversal With Reduced Bypass Flow Restriction," Columbia University Heat Transfer Research Facility, CU-HTRF-95-03 (Final Report Vols. I and II).

- [9] Cheng, L.Y., 1995, "Flow Reversal Limited Operating Power for the HFBR," Reactor Division, BNL Calculation, SEG-57-0.
- [10] Cheng, L.Y., 1995, "Comparison of RELAP5 and a Drift Flux Model in the Calculation of Multi-Channel Flow Reversal," BNL Memorandum.

TABLE 1

HEATED SECTION DIMENSIONS

<u>Single Sided Heater</u>	
width of channel	2.160 inches
channel gap	0.10 - 0.113 inches
channel length	24.00 inches
heater width	2.25 inches
heater length	22.750 inches
heater thickness	0.050 inches
<u>Double Sided Heater</u>	
width of channel	2.160 inches
channel gap	0.098 - 0.116 inches
channel length	24.00 inches
heater width	2.25 inches
heater length	22.750 inches
thickness of heaters	0.025 inches

TABLE 2.1

SUMMARY OF FIRST TEST SERIES' SINGLE-SIDED HEATING

TEST NUMBER	ORIFICE DIAMETER (inches)	BYPASS" RATIO	WATER LEVEL (ft.)	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	NOMINAL POWER (kW)	FR POWER (kW)	TRIP POWER (kW)	TEST*** OUTCOME
B021393F	0.199	2:1	14.43	130	40	7.0	7.30	-	FR
B021393H	0.199	2:1	14	130	40	7.5	-	7.95	T/C #1
B021393I	0.199	2:1	14	130	30	7.5	7.90	-	FR
B021393K	0.199	2:1	14	130	30	8.0	-	8.70	T/C #1,4
B021393N	0.199	2:1	14	130	Pump trip	9.0	9.35	-	FR
B021393P	0.199	2:1	14	130	Pump trip	10.0	10.4	10.65	FR then T/C #1
B021393O	0.199	2:1	14	130	Pump trip	10.5	10.85	11.05	FR then T/C #1
B021393Q	0.199	2:1	14	110	40	8.0	8.65	9.20	FR then trip after 4 min.
B021393R	0.199	2:1	14	110	40	9.0	-	9.50	Voltage
B030493B	0.199	2:1	14	130	40	7.0	7.10	-	FR
B030493A	0.199	2:1	14	130	40	7.5	-	8.4	T/C #2 and Voltage
B030493D	0.199	2:1	3.67	130	40	7.0	7.15	-	FR
B030493E	0.199	2:1	3.67	130	40	7.5	-	8.10	T/C #1
B080394B	0.199	2:1	14	130	40	7.0	7.40	-	FR
B080394A	0.199	2:1	14	130	40	7.5	-	8.00	Voltage

TABLE 2.1

SUMMARY OF FIRST TEST SERIES' SINGLE-SIDED HEATING

TEST NUMBER	ORIFICE DIAMETER (inches)	BYPASS** RATIO	WATER LEVEL (ft.)	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	NOMINAL POWER (kW)	FR POWER (kW)	TRIP POWER (kW)	TEST*** OUTCOME
B080394E	0.129	5:1	14	130	40	6.2	6.70	-	FR
B080394D	0.129	5:1	14	130	40	6.5	-	7.10	Voltage
B080394G	0.28	1.5:1	14	130	40	7.5	8.2	-	FR
B080394H	0.28	1.5:1	14	130	40	7.8	-	8.55	T/C #1, 2 and Voltage

Notes:

* Test loop configuration shown in Figure 3 was used.

** The ratio of flow in test section to flow in bypass under initial conditions. Combined initial flow rate was 3 gpm for all tests.

*** FR signifies absence of trip for 30 seconds after flow reversal. T/C or voltage indicates that a plate temperature excursion or plate voltage excursion caused trip. Number of T/C indicates thermocouple location on plate by a number 1 to 9 starting at top of plate.

TABLE 2.2

SUMMARY OF FIRST TEST SERIES* - TWO-SIDED HEATING

TEST NUMBER	ORIFICE DIAMETER (inch)	BYPASS** RATIO	WATER LEVEL (ft.)	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	NOMINAL POWER (kW)	FR POWER (kW)	TRIP POWER (kW)	TEST*** OUTCOME
B061293E	0.199	2:1	14	130	40	8.0	8.7	-	FR
B061293G	0.199	2:1	14	130	40	8.5	-	9.4	Voltage
B061293H	0.199	2:1	14	130	Pump Trip	10.5	11.4	12.0	FR then Voltage
B061293J	0.199	2:1	14	150	40	6.5	6.7	-	FR
B061293I	0.199	2:1	14	150	40	7.0	-	7.7	T/C
B061293L	0.199	2:1	14	130	60	6.5	7.3	-	FR
B061293K	0.199	2:1	14	130	60	7.0	-	7.85	Voltage

Notes:

* Test loop configuration shown in Figure 3 was used.

** The ratio of flow in test section to flow in bypass under initial conditions. Combined initial flow rate was 3 gpm for all tests.

*** FR signifies absence of trip for 30 seconds after flow reversal. T/C or voltage indicates that a plate temperature excursion or plate voltage excursion caused trip. Number of T/C indicates thermocouple location on plate by a number 1 to 9 starting at top of plate.

TABLE 2.3

SUMMARY OF HELIUM EFFECTS TESTS'

TEST NUMBER	HELIUM	UPPER* PLENUM VOID FRACTION	ORIFICE DIAMETER (inches)	BYPASS** RATIO	COASTDOWN TIME (sec)	NOMINAL POWER (kW)	FR POWER (kW)	TRIP POWER (kW)	TEST*** OUTCOME
B101694B	NO	0.0	0.199	1.42:1	40	7.5	7.85	-	FR
B101694E	YES	0.11	0.199	1.42:1	40	7.0	7.60	-	FR
B101694C	NO	0.0	0.199	1.42:1	40	8.0	-	8.90	Voltage
B101694D	YES	0.13	0.199	1.42:1	40	7.5	-	8.10	Voltage & T/C #1
B101694G	NO	0.0	0.199	1.42:1	60	6.5	7.00	-	FR
B101694H	YES	0.065	0.199	1.42:1	60	6.5	6.70	-	FR
B101694F	NO	0.0	0.199	1.42:1	60	7.0	-	7.75	Voltage
B101694I	YES	0.045	0.199	1.42:1	60	7.0	-	7.50	Voltage
B101694L	NO	0.0	0.129	2.78:1	40	6.4	6.95	-	FR
B101694M	YES	≈0.0	0.129	2.78:1	40	6.5	7.00	-	FR
B101694K	NO	0.0	0.129	2.78:1	40	6.6	-	7.20	Voltage
B101694N	YES	0.038	0.129	2.78:1	40	7.0	-	7.75	Voltage

Notes:

- # All tests were done with water level at 14' above the inlet section, an inlet water temperature of 130°F, and single-sided heating. Test loop configuration shown in Figure 4.
- * Approximate void fraction at the time of flow reversal; calculated from a pressure difference measurement in the upper plenum.
- ** The ratio of flow in test section to flow in bypass under initial conditions. Combined initial flow rate was 3.4 gpm for all tests.
- *** FR signifies absence of trip for 30 seconds after flow reversal. T/C or voltage indicates that a plate temperature excursion or plate voltage excursion caused trip. Number of T/C indicates thermocouple location on plate by a number 1 to 9 starting at top of plate.

TABLE 2.4

SUMMARY OF EXTENDED BYPASS RATIO TESTS*

TEST NUMBER	TOTAL INITIAL FLOW (gpm)	BYPASS* RATIO	WATER** LEVEL (ft.)	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	NOMINAL POWER (kW)	FR POWER (kW)	TRIP POWER (kW)	TEST*** OUTCOME
B081395E	3.0	2:1:0	14	130	40	9.0	9.45	-	FR
B081395F	3.0	2:1:0	14	130	40	9.5	-	10.25	T/C #1
B081395K	8.8	1:3.4:0	14	130	40	14.0	14.35	-	FR
B081395L	8.8	1:3.4:0	14	130	40	14.5	-	15.00	T/C #9
B081395M	10.0	1:3.4:0.6	14	130	40	14.5	-	14.9	T/C #9
B081395N	10.0	1:3.4:0.6	14	130	40	14.0	14.2	-	FR
B081395O	10.0	1:3.4:0.6	14	130	30	14.5	-	15.02	T/C #9
B081395U	4.2	2:1:1.2	14	130	40	11.5	12.0	-	FR
B081395V	4.2	2:1:1.2	14	130	40	12.5	-	13.75	Voltage
B081795C	10.0	1:3.4:0.6	14	130	Pump Trip	19.0	19.8	-	FR
B081795D	10.0	1:3.4:0.6	14	130	##	21.0	-	21.65	Voltage

Notes:

+ Test loop configuration shown in Figure 5.

* The ratio of flow in test section to flow in primary bypass to flow in secondary bypass under initial conditions.

** Height of column of water above top of the inlet section.

*** FR signifies absence of trip for 30 seconds after flow reversal. T/C or voltage indicates that a plate temperature excursion or plate voltage excursion caused trip. Number after T/C indicates thermocouple location on plate by a number 1 to 9 starting at top of plate.

A voltage trip occurred while power was being raised and before pump was shut off.

TABLE 3

LIST OF RELAPS SIMULATIONS OF FLOW REVERSAL TESTS

RELAPS RUN NO.	REFERENCE* TEST NO.	TEST* OUTCOME	CHANNEL* POWER (kW)	ORIFICE** DIAMETER (in.)	BYPASS** RATIO	NUMBER SIDES HEATED	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	MAXIMUM** VOID FRACTION
101	B021393F ⁽¹⁾	FR	7.0	0.199	2:1	1	130	40	0.696
102	B021393H ⁽¹⁾	Trip	7.6	0.199	2:1	1	130	40	0.761
103	B021393I ⁽¹⁾	FR	7.6	0.199	2:1	1	130	30	0.716
104	B021393K ⁽¹⁾	Trip	8.4	0.199	2:1	1	130	30	0.789
107	B021393Q ⁽¹⁾	FR	8.3	0.199	2:1	1	110	40	0.704
108	B021393R ⁽¹⁾	Trip	9.1	0.199	2:1	1	110	40	0.771
109	B030493D ⁽¹⁾	FR	6.9	0.199	2:1	1	130	40	0.762
110	B030493E ⁽¹⁾	Trip	7.8	0.199	2:1	1	130	40	0.829
112	B080394E ⁽¹⁾	Trip	6.8	0.129	5:1	1	130	40	0.884
113	B080394D ⁽¹⁾	FR	6.4	0.129	5:1	1	130	40	0.860
114	B080394G ⁽¹⁾	FR	7.9	0.28	1.5:1	1	130	40	0.739
115	B080394H ⁽¹⁾	Trip	8.2	0.28	1.5:1	1	130	40	0.766
302	B101694B ⁽²⁾	FR	7.5	0.199	1.42:1	1	130	40	0.819
303	B101694C ⁽²⁾	Trip	8.5	0.199	1.42:1	1	130	40	0.904
304	B101694F ⁽²⁾	Trip	7.4	0.199	1.42:1	1	130	60	0.851
305	B101694G ⁽²⁾	FR	6.7	0.199	1.42:1	1	130	60	0.777
306	B101694K ⁽²⁾	Trip	6.9	0.129	2.78:1	1	130	40	0.895
307	B101694L ⁽²⁾	FR	6.7	0.129	2.78:1	1	130	40	0.894

TABLE 3 (CONTINUED)

LIST OF RELAP5 SIMULATIONS OF FLOW REVERSAL TESTS

RELAP5 RUN NO.	REFERENCE* TEST NO.	TEST* OUTCOME	CHANNEL* POWER (kW)	ORIFICE** DIAMETER (in.)	BYPASS** RATIO	NUMBER SIDES HEATED	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	MAXIMUM** VOID FRACTION
201	B061293E ⁽¹⁾	FR	8.3	0.199	2:1	2	130	40	0.784
202	B061293G ⁽¹⁾	Trip	8.9	0.199	2:1	2	130	40	0.819
204	B061293I ⁽¹⁾	Trip	7.3	0.199	2:1	2	150	40	0.824
205	B061293J ⁽¹⁾	FR	6.4	0.199	2:1	2	150	40	0.743
206	B061293K ⁽¹⁾	Trip	7.5	0.199	2:1	2	130	60	0.775
207	B061293L ⁽¹⁾	FR	6.9	0.199	2:1	2	130	60	0.701
1	B081395E ⁽²⁾	FR	9.0	-	2:1:0	1	130	40	0.713
2	B081395F ⁽²⁾	Trip	9.8	-	2:1:0	1	130	40	0.774
10	B081395K ⁽²⁾	FR	13.8	-	1:3.4:0	1	130	40	0.860
21	B081395N ⁽²⁾	FR	13.8	-	1:3.4:0.6	1	130	40	0.668
6	B081395U ⁽²⁾	FR	11.5	-	2:1:1.2	1	125	40	0.55
5	B081395V ⁽²⁾	Trip	13.2	-	2:1:1.2	1	130	40	0.667
11	B081795C ⁽³⁾	FR	19.0	-	1:3.4:0.6	1	130	1.5	0.718

Notes:

- * The number in parenthesis after the test number is the test loop configuration: (1) refers to Figure 3; (2) refers to Figure 4; (3) refers to Figure 5.
- # FR means a successful flow reversal without a power trip for 30 seconds after initiation of flow reversal.
- + Channel power corresponds to either the flow reversal power or the trip power given in Tables 2. The channel power listed includes a reduction of 4% and 5% to account for heat loss from the single-sided and two-sided heaters respectively.
- ** A numerical value indicates orifice diameter in bypass path in test configurations (1) and (2). A (-) indicates use of throttling valve in bypass path.
- ## Refers to ratio of flow rates under initial conditions. First number applies to section flow, second number applies to primary bypass flow and third number, if present, applies to secondary bypass flow in test configuration 3.
- + + Maximum time-averaged void fraction during the 10 second interval following reversal in RELAP5 calculation. The time averaging period is two seconds.

Figure 1 HFBR Vessel Showing Normal Flow Direction

Figure 2 Schematic of the Flow Reversal Test Loop

Figure 3 Schematic of Test Loop for First Test Series

Figure 4 Schematic of Test Loop for Helium Tests

Figure 5 Schematic of Test Loop for Extended Bypass Ratio Tests

ITEM NO.	QTY.	DESCRIPTION
1	-	PLEXIGLAS
2	-	SIDE RAIL (ASBESTOS PHENOLIC)
3	-	KAPTON TAPE (4 LAYERS)
4	-	ALUMINUM HEATER STRIP (WIDTH = 2.25)
5	-	INSULATOR (PEEK)

NOTE:

1. ALL DIMENSIONS ARE NOMINAL VALUES AND IN INCHES.

Figure 6 Cross-Section of the Single-Heater Test Section

1. COASTDOWN STAGE
2. VAPOR GENERATION STAGE
3. OSCILLATORY FLOW STAGE
4. NATURAL CIRCULATION FLOW STAGE

Figure 7 Stages of the Flow Reversal Process

RELAP5 Run # 101 (No Dryout)
One-sided Heating

Figure 8 Typical Trace of Time Averaged Channel Void Fraction

Channel Average Void Fraction Corresponding To Dryout Power Predicted By Various Correlations

Figure 9

Figure 10 Decay Power vs. Time After Shutdown

Cover Gas Pressure
(Base Case 64.05 MW)

Figure 11 Cover Gas Pressure vs. Time After Accident Initiation

Figure 12 Primary Flow Rate vs. Time After Accident Initiation

Mass Flow Rate at Top of Heated Channel
(Base Case 64.05MW)

Figure 13 Mass Flow Rate At Top of Heated Channels vs. Time

Mass Flow Rate at Bottom of Heated Channel
(Base Case 64.05MW)

Figure 14 Mass Flow Rate at Bottom of Heated Channels vs. Time

Instantaneous Channel Void Fraction (Base Case 64.04 MW)

Figure 15 Instantaneous Channel Void Fraction vs. Time

Fri Apr 7 16:55:32 1995

Time Averaged Void Fraction

Figure 16 Time Averaged Channel Void Fraction vs. Time (Average Channel Group 2)

Fri Apr 7 17:00:23 1995

Time Averaged Void Fraction

Figure 17 Time Averaged Channel Void Fraction vs. Time (Average Channel Group 6)

Figure 18 Time Averaged Channel Void Fraction at 2 Power Levels (Pump Trip Test Simulations)

APPENDIX A

TEST PROGRAM

A. GENERAL OBJECTIVES

The test program was developed with the assistance of consultants Richard Lahey and Hans Fauske, experts in the thermal-hydraulic area. The program was designed to capture, as closely as possible, the essential features of the flow reversal transient in the reactor.

1. Scaling to achieve similar thermal-hydraulic responses.
2. Spatial variation of heat generation.
3. Rate of flow coastdown on loss of pumping power.
4. Effect of flow impedance of flow reversal valves.
5. Effect of liquid level.
6. Effect of pressure.
7. Effect of initial water temperature.
8. Effect of helium evolution on depressurization.

Another objective of the test program, separate from the issue of prototypicality, was to provide a means of visualizing the flow reversal process. This was accomplished in one series of tests by designing the test channel with one side heated and one side transparent. Recordings were taken with a video camera.

The test program, as originally outlined, involved multichannel testing following completion of the single channel tests. However, after the single channel tests and modeling effort were completed, it was concluded that the expense and delay associated with the fabrication of a multichannel loop could not be justified. Simulation of multi-channel effects is discussed in Section C.5 of this appendix.

B. DESCRIPTION OF TESTS

Three series of flow reversal tests were conducted under somewhat different test loop configurations. These changes were made to extend the range of test conditions to include the investigation of the helium void effect and the effect of very low impedance in the bypass path. The information given in B.1, B.2 and B.3 below applies to the first series of tests. The modifications for the helium void effect are described in Section

B.4. Section B.5 describes the modifications to lower the bypass path impedance.

1. Test Loop

The tests were performed with an electrically heated section representing the core, an orifice representing the flow reversal valves, a variable speed pump to simulate the flow coastdown, and auxiliary piping and equipment to simulate other pertinent structures in the reactor vessel [A1]. Figure A1 shows the various components of the test loop and their general arrangement. The test loop was set up to preserve the vertical height of the natural circulation flow path in the HFBR vessel. The heated section was a full-size mockup of a typical channel in a HFBR fuel element. The flow areas of the test loop were scaled to correspond to a typical coolant channel in the HFBR. The top of the upper plenum region was open to the atmosphere. Demineralized water was the working fluid of the test loop.

The fuel plates were simulated in the test by 6061 aluminum plates of similar thickness and powered by direct DC heating. The heated section was 2 feet in height. Two separate heater arrangements were used in the experiments. The single-sided arrangement had one heater plate and a transparent Plexiglas separated by the coolant gap. The double-sided heater had a heater plate on each side of the coolant gap. The cross-sectional view of the single-sided heater is shown in Figure A2. The channel gap was maintained by two spacer rails installed along the side edges of the channel, overlapping the heater plate(s) by ~0.05 inch. The dimensions of the two heated sections are shown in Table A1.

The heated section was powered by a set of direct current generators. The low electrical resistance of aluminum resulted in a voltage drop of only 2 volts across the length of the heater plates. At low voltages the generator output was prone to drift. A ballast, made up of a twenty-foot length of water cooled stainless steel pipe, was installed in series with the heater plate(s) to raise the total resistance seen by the generator and stabilize the output voltage.

An orifice was used to simulate the flow impedance of the four flow reversal valves in the reactor and other core bypass paths. The nominal flow condition of the four open valves and other paths was simulated by a 0.199 inch diameter orifice. The nominal flow split between the heated section and the bypass was 2:1. Additional tests were done with other orifice sizes to determine the effect of bypass flow impedance.

The initial flow through the heated section and the bypass orifice was provided by an eccentric screw pump which has the

characteristics of a positive displacement pump. The pump capacity is 10 gpm. The effect of flow coastdown was created by using a programmable speed controller to vary the rotational speed of the pump motor.

2. Instrumentation

The instrumentation layout is shown in Figure A3 and Table A2 provides functional information. The test loop was instrumented to monitor the temperature, pressure, and flow rate of the coolant. Each heater plate was monitored for current, voltage, and wall temperatures at nine locations. All data were collected digitally by a computer controlled data acquisition system. In addition, video recordings were made for all the single-sided heater tests.

The total loop flow rate was measured by a 0.5-inch turbine flowmeter (FLI1) located downstream of the circulation pump discharge. Two bi-directional turbine flowmeters were installed in the bypass line and the reflector section to measure the bypass flow (FBP) and the test section flow (FRE). The turbine flowmeters were calibrated in place for single-phase water flow in the range of 0.2 - 3.0 gpm. In case of two-phase flow or high frequency flow oscillation both the flow rate and the directional signals from the flowmeters became difficult to interpret. A differential pressure transducer (DO1) was installed across the bypass orifice plate as a backup for the bypass flow measurement. A similar transducer (DRE) was installed across the reflector turbine flowmeter (FRE).

Three pressure transducers were used to measure the absolute pressure at the inlet section (PTIB), the lower plenum (PTOB), and the upper plenum (PTP1). Five differential pressure transducers were used to measure the pressure drop along the heated section. One transducer measured the pressure drop in each quarter of the heated section (DT1, DT2, DT3, DT4), and one was for the overall heated section pressure drop measurement (DT5). The five pressure taps were located on the narrow side of the heated channel. The differential pressure indications did not include the hydrostatic head because the zero reading was taken when the test loop and the pressure lines were filled with water. Hence, the differential pressure transducers only measured the frictional and acceleration pressure drop.

The water temperature was monitored by two types of sensors, namely, iron-constantan thermocouples and resistance temperature detectors (RTD). Test section inlet and exit temperatures were measured by RTD's located in the inlet section (RTI1) and the lower plenum (RTO1). In addition, two thermocouples (JTI1 and JTO1) were installed at the same

locations as backup measurements. Two other RTD's were located in the upper plenum (RTP1) and the reflector region (RTR1) to monitor the trend of temperature variation during the course of flow reversal and natural circulation. For the same purpose, three additional thermocouples were used in the lower plenum (JRB1), the bypass line (JRP1) and at the junction, upstream of the pump suction, where the fluid streams from the reflector and the bypass sections recombined (JRB1).

The wall temperatures of the heater plates were measured by 0.064-inch thermocouples. Each thermocouple was installed through an eyelet pinned directly to the heater plate. Nine thermocouples were evenly distributed along the middle of the heater plate at 2.75 inches interval. They were identified from top to bottom by numbers EW01 to EW09 for the single-sided heater, and EW101 to EW109 for the first plate and EW201 to EW209 for the second plate of the double-sided heater.

The heater plates were protected from overheating during the flow reversal experiments by two types of power trips, a temperature trip and a voltage trip. Depending on the power level, all wall temperature trips were set at a temperature of about 30 - 40 degrees F above the test section exit saturation temperature. Typical temperature trip setpoint was between 260 to 280 °F. There was an increase in the electrical resistance of the aluminum plates as their temperatures rose during the course of the flow reversal transient. The upward drift in voltage was about 5 - 7 % for a coolant temperature rise from 130°F to saturation. The voltage trip was set at 10 % above the initial operating voltage. This setting was found to be high enough to avoid spurious trips while protecting the heater plates from overheating.

Power to the test section was calculated from the measured current and voltage applied to the heater plates. The current was measured separately by two calibrated shunts. The test section voltage was measured by two separate calibrated voltage divider setups. For the double-sided heater the two heater plates were installed in series. An excursion in the wall temperature or an over-shoot in the voltage across a heater plate would result in an automatic power cut off to the heated section. This was used as an indication that the thermal limit had been exceeded.

3. Test Procedure

In each test, flow reversal in the heated section was initiated by a reduction in the forced flow provided by the circulation pump. The pump flow was ramped down linearly in time to simulate the coastdown of the HFBR primary pumps from

the shutdown flow rate. A number of parameters were varied in the tests to examine their effects on the thermal limit. Among the parameters varied were the rate of flow coastdown, inlet subcooling, water level in the upper plenum, bypass ratio (ratio of initial flow through the heated section to initial flow through the bypass orifice), and single versus double-sided heating. The baseline test conditions were:

Mode of heating: single-sided

Water level: 14 feet above the top of the inlet section

Inlet temperature: 130 °F, entering the heated section

Coastdown time: 40 seconds

Bypass ratio: 2:1

For a given set of test conditions the flow reversal experiment was repeated at increasing power levels to the heated section until the thermal limit was bracketed within a 0.5 kW interval. The power was maintained at the specified level throughout each test run. However there was a small upward drift in power due to the changing electrical resistance of the heated section as the temperature increased. A successful flow reversal was defined as a test where natural circulation cooling was sustained without a power trip for more than 30 seconds after flow reversal.

4. Modifications for Helium Evolution Tests

Since the HFBR vessel is pressurized by helium to 200 psig during normal operation the coolant is saturated with dissolved helium. The vessel is automatically depressurized on loss of coolant and the dissolved helium will evolve from the coolant in the form of small bubbles. The maximum anticipated void fraction is $\approx 15\%$ [A2]. The helium bubbles may influence the heat transfer and coolant flow in the heated channels during flow reversal.

Since the flow reversal test loop was not designed to operate at 200 psig, the helium dissolution effect was simulated by preparing a saturated solution of helium in water at 200 psig in a separate tank and feeding the helium saturated water at a controlled rate to the test loop through a supply valve which dropped the pressure in the water to close to atmospheric [A3]. The flow reversal test was initiated as soon as the test loop was filled with the helium-water mixture to minimize the coalescence and separation of the evolved helium that would normally occur after a period of time. The void fraction was determined from the static pressure difference between two elevations in the upper plenum of the test loop.

During the first tests with helium, large gas bubbles were observed to rise from the bottom of the heated section when the forced flow had coasted down to almost zero. The gas bubbles were from the helium gas accumulated in the vertically oriented open space in the bottom plenum adapter section. In the HFBR vessel, there is no confined vertical space below the core region and hence any significant accumulation of helium in the lower plenum region is unlikely.

Three modifications were made to the test loop to limit helium accumulation in the bottom plenum section. The vertical section of the bottom plenum was shortened. A filler piece was inserted in the vertical section to eliminate extra open space. The horizontal portion of the bottom plenum was tilted upward at a 10 degree angle to prevent helium accumulation. The modified test loop is shown in Figure A1.

The preliminary helium test not only indicated a need to limit the helium accumulation but also a need to conduct further tests to study the effects of bypass flow restriction. An earlier test result (1993) [A1] indicated a slightly higher thermal limit for a smaller bypass orifice. This result was contrary to the expectation that an increase in flow restriction would lower the thermal limit. When flow reversal tests conducted as part of the preliminary helium tests indicated a slightly lower thermal limit with increased flow restriction, it was decided that further tests be done with a variety of bypass flow restrictions to clarify the issue before modifying the loop for the helium tests. In these tests care was exercised not to disturb the channel gap clearance which could be affected (within specified tolerances) by adjustments made to the test section. In the earlier 1993, test series, such adjustments may have affected gap clearance sufficiently to cause the higher thermal limit. The results of the tests in which the bypass orifice size was varied, confirmed the expectation that a smaller (more restrictive) bypass orifice reduces the thermal limit.

5. Modification to Lower the Bypass Path Impedance

After reviewing the results of previous tests and analyses it was concluded that the data base should be expanded to develop more confidence in the RELAP5 simulations of the tests and the ability to predict dryout in the multi-channel HFBR core. As discussed in detail in Section C.5, the multichannel core with channel to channel variations in heating rates is equivalent in some respects to a single channel with a low impedance in the bypass path. One measure of the bypass impedance is the bypass ratio which as noted earlier is the ratio of flow in the channel to flow in the bypass path under initial flow conditions. The baseline condition for the bypass ratio is 2:1 which is the ratio of flow in the core to the flow in

bypass paths when all channels are in downflow. However, the cooler channels can be considered as part of the bypass path since they are still in downflow when the hot channels reverse. The effective bypass ratio in this situation is much smaller. If only the hottest channels are considered it is estimated that the effective bypass ration is about 1:14. Achieving this bypass ratio would require a substantial increase in the size of the pump and major changes to the loop and was considered impractical. Instead a compromise value of 1:3.4 was selected. This was judged to be sufficiently different from the earlier tests to achieve the desired effect.

Several modifications to the loop were made as can be seen from the Figure A5 which is a schematic of the modified loop [A4].

1. The positive displacement pump was replaced with a larger capacity pump. The diameter of the supply and return line to the pump was increased and the flowmeter in the pump discharge line was replaced with one of increased capacity. Neither of these changes affected the bypass path flow impedance.
2. The bypass line (the line containing valve V2 in Figure A5) originally had a 1/2" turbine flow meter and an orifice to simulate the flow reversal valves. The flow meter and orifice plate was eliminated and replaced with a valve (V2) for flow adjustment.
3. The 1/2" turbine flow meter in the reflector section was replaced with a section of 2 1/2" diameter pipe.
4. A magnetic flowmeter which consisted of a foot long section of 1/2" diameter pipe was installed in the vertical section of the reflector.
5. A line was added from the pump discharge (near flowmeter FLI 1) to the line below the heated section. This was a 1" line which contained a 3/4" turbine flowmeter and a gate valve. This line was intended to simulate another aspect of the multiple channels in the core. While in downflow the water temperature change from inlet to outlet is determined by the average core power rather than the hot channel power. Thus the water temperature entering the bottom of the channels when reversal occurs would be lower than would be the case with a single channel test with a hot channel. This secondary line injects unheated water into the region below the heated section at a rate that when mixed with the water from the heated section, will result in an average temperature that will be approximately equal to the water temperature

below the core. An earlier version of this bypass line was located such that the line ran from above the inlet section to below the heated section. This path would exactly simulate an unheated parallel channel. However it was not possible to achieve the necessary flow with this arrangement so that location of the high pressure end of the line was changed. The ratio of the channel flow to this bypass flow was 1:0.6.

C. COMPARISON OF TEST AND REACTOR CONDITIONS

In Part A the general objectives of the test program were outlined. How these objectives were met are discussed below.

1. Initial Conditions for the Test

In principle, the initial conditions for the tests should match the conditions in the HFBR at the beginning of flow coastdown. However the relatively high heat transfer coefficients with the core, the low thermal inertia of the fuel element and slow flow transients result in essentially steady state conditions existing from the start of coastdown where coolant velocities in the core are 35-40 ft/sec to shutdown cooling flow levels where velocities are 2-3 ft/sec. This fact simplified the experimental requirements by making it possible to initiate the tests at relatively low flow rates (≈ 3 gpm). This flow rate was analogous to a total reactor flow rate of 1300 gpm which is the flow rate when a single pony motor driven pump provides the shutdown cooling flow.

During the flow coastdown period, the water temperature at the inlet to the core will remain constant at the full power steady state value of 130°F (nominal) until the water at the heat exchanger outlet has been transported to the core inlet. The water that enters the core after this time will be at or below 130°F depending on the timing of the reactor trip with respect to the initiation of pump coastdown. Conducting the base case test at a constant inlet temperature of 130°F will therefore be conservative. However, to assess the magnitude of the temperature effect and to determine the effect of variations in full power core inlet temperature, flow reversal tests were also performed at 110 and 150°F.

2. Scaling of Test Loop

The scaling criteria for the test loop were based on the similarity rules derived by Ishii and Kataoka [A5]. The following assumptions were used in establishing the scaling criteria.

- a. Identical coolant channel dimensions.

- b. Dynamic similarity (inertia and pressure loss) preserved for the natural circulation loop. It should be noted that in the first and second series of tests (Figure A3, A4) the pressure loss due to a turbine flow meter in series with the test section was overlooked. For these tests the pressure loss in the loop was relatively higher than in the reactor. In the last test series (Figure A5) the turbine flowmeter was replaced with a low impedance magnetic flowmeter. In this latter test configuration the pressure losses were similar to the reactor losses.
- c. Similar thermal inertia, particularly in the large volume regions which are the upper and lower plenum and reflector.

With respect to the channel dimensions there are 4 different channel sizes in the HFBR fuel element. They all have the same height (24") and width (2.46") but have nominal gaps of 0.100", 0.118", 0.108" and 0.096". A nominal value of 0.100" was selected for the test channel gap. Because it was necessary to allow for thermal expansion of the heated plates, the plate could not be rigidly fixed and as a result there was some uncertainty in the channel gap. The design specification resulted in a gap that could vary between 0.10" and 0.113" for the single sided heater and between 0.098" and 0.116" for the two-sided heater. In analyzing the test data, the maximum gap value was conservatively assumed. A channel with a larger flow area will have a larger heat removal capacity, all other things being equal.

In Table 1 it is seen that the heated width of the reactor channel (2.25") is matched in the test channel. However the reactor channel width (2.46") is larger than the heated width while the test channel width (2.16") is slightly smaller than the heated width. The original design of the test section called for making the channel and heated widths the same, 2.25". This was a design simplification which was considered to be conservative. However when buckling of the heated plate was experienced during preliminary testing, the design was modified again by using spacer rails along the side edges of the plate to maintain the gap. These rails overlapped the heater plate(s) by about 0.05" and thereby reduced the channel width. This modification was also considered conservative since it reduced the heat transfer area exposed to the coolant and thereby increased the heat flux.

Details of the scaling analysis are given in Reference A6.

3. Spatial Variation of Heat Generation in Fuel

In the reactor the heat generation rate varies from fuel plate to fuel plate and within a single plate. This applies to full

power operation and to shutdown conditions which are of concern here. The ratio of peak local heat generation rate in the hot plate to the average in the hot plate is 1.80 [A7]. It was not feasible to simulate this spatial variation in the tests. The electrically heated aluminum plates were of uniform cross-section so that the heat generation was uniform across the width and length of the plate. However the importance of span wise variations in the heating rate could be assessed by comparing the results of tests in which one side of the channel was heated to the case where both sides were heated. Thus for 2 tests conducted at the same total channel power, the heat flux for the test with one side heated is twice the flux of the 2 sides heated. The effect of axial variation in heating rate was evaluated using the RELAP5 Code and is discussed in Appendix C.

With regard to the tests in which both sides of the channel were heated, the thickness of the plate was 0.025 in., which is one-half of the fuel plate thickness. The half thickness is used to reflect the fact that in the reactor each plate is cooled on two sides by adjacent channels whereas only one channel is used in the test.

In the tests in which the channel was heated on one side only, the thickness of the heated plate was 0.050 in. The purpose here was to match the transient characteristics of the plates in the two sided heating tests. Thus for the same total channel power, the heat generation per unit volume of plate would be the same in both cases.

4. Rate of Flow Coastdown

A flywheel was mounted on each of the primary pump motors in the HFBR because of concern about downflow stability at the design flow rate of the shutdown pump. The flywheel also delayed the onset of flow reversal in the event the shutdown pump failed. This delay was beneficial in that it resulted in flow reversal occurring at a reduced afterheat power. Another consequence of the flywheel installation, that was not recognized at the time, is that the slower coastdown would tend to impede the flow reversal process. It was therefore considered important that this effect be examined in the test program. Flow coastdown measurements made on the reactor were used as a basis for establishing test conditions. These measurements were made long after the reactor was shutdown so that there was little afterheat present. The initial condition for the measurement was a flow rate of about 1300 gpm provided by a pony motor driven primary pump. Coastdown to zero flow occurred 40 seconds after the pump was shutdown [A8]. This coastdown time was simulated in the test by means of a screw pump with a programmable speed controller to vary the speed of the pump motor.

As noted above the flow decay measurement on the reactor was made without decay heat present. If significant decay heat were present the flow rate would fall more rapidly when flow reversal occurred, because the reactor pumps are centrifugal rather than positive displacement pumps. The test program included tests at coastdown times of 30 and 60 seconds to determine the importance of this variable.

5. Flow Reversal Valve Impedance

Although the flow reversal valves are closed when the main pumps are operating at full flow, they will open at the reactor conditions corresponding to the initial conditions of the tests. It is assumed here that the shutdown pumps have also been turned off since the valves would not open if the shutdown pumps were running.

With the valves open, a fraction of the flow delivered by the primary pump(s) will bypass the core through the open valves. In addition to the valves there are other bypass paths. These include paths for control blade cooling and those formed by the spacing between the transition plate and the internal structures that penetrate it. The flow pressure drop characteristics of the flow reversal valve are based on measurements made on a prototype valve. The other bypass flows have been calculated. At a total flow rate of 1300 gpm about 18% passes through the open valves, 15% passes through the other bypass paths and the balance, 67%, passes through the core. Thus the ratio of core flow to total bypass flow is 2:1.

In the test, 3 gpm corresponded to a total flow rate in the reactor of 1300 gpm. An orifice was used to simulate the flow reversal valves and other bypass paths. An orifice size was selected to achieve the 2:1 ratio of flow rate in the heated channel to orifice flow rate.

When the pumps stop and flow reversal and natural circulation ensue, these bypass paths provide the return leg of the natural circulation loop. The flow impedance of these paths will affect the dynamics of flow reversal. To determine the importance of this parameter tests were conducted with a range of orifice sizes which corresponded to flow rate ratios from 5:1 to 1:3.4.

It should be noted that a single channel test at the maximum channel heating rate in the core does not reflect the beneficial effect of the many parallel channels that exist in the reactor and operate at lower heating rates. Flow reversal will not occur at the same time in all the channels. The return path for flow from the channel which reverses first will include the other channels still in downflow as well as

the flow reversal valves and bypass paths. This effect is equivalent to a reduction in the flow impedance of the bypass path. From this viewpoint, the single channel tests with a bypass ratio of 2:1 represents a conservative bound on the reactor conditions. This issue will be discussed in greater detail in Appendix C.

6. Effect of Liquid Level

The reactor vessel liquid level at which flow reversal occurs will depend on the accident scenario. If the accident does not involve a loss of coolant, the level will remain at its nominal operating value of about 14 feet above the top of the inlet section of the fuel element. In the LOCA scenarios analyzed, the liquid level has dropped no more than 4 feet by the time flow reversal has occurred. After flow reversal, the water level continues to drop, depending on the location of the leak and could fall to a point about 2 feet above the top of inlet section of the fuel element in a leak in a beam tube. This level corresponds to the top of the thermal shield cavity.

In order to bound the effect of liquid level, tests were done with the level at 14 feet and at 3.7 feet above the top of the inlet section to the test section.

7. Effect of Pressure

Depressurization of the primary system occurs automatically in the HFBR in all loss of forced flow cooling accidents. The depressurization is accomplished by opening a valve in the helium cover gas and venting the gas to atmospheric. In some accidents flow reversal will occur when depressurization is complete, i.e., the cover gas is at atmospheric pressure. In others there may be a residual pressure above atmospheric at the time of flow reversal. The current reactor power level is based on the conservative assumption that the decay heat removal mechanism is by counter-current flow with coolant entering the core from the top only [A9]. In flooding limited models an increase in pressure will result in an increase in heat removal capacity at least in the pressure range of interest here. Other correlations of CHF (critical heat flux or dryout) in boiling in narrow rectangular channels indicate that increases in pressure cause an increase in CHF [A10, A11]. Accordingly conducting the tests at atmospheric pressure is considered conservative.

8. Effect of Helium Evolution

In the reactor, the amount of helium gas dispersed in the reactor coolant at the time of flow reversal depends on the rate of depressurization, the coolant flow rate and the

kinetics of helium dissolution. Since those factors are scenario dependent and in some cases difficult to quantify a bounding approach is taken to determine the quantity of dispersed helium present. It is assumed that during the depressurization and coastdown period (1) all the helium that can come out of solution, based on equilibrium considerations, will come out and (2) that this precipitated helium does not escape to the cover gas but remains dispersed as bubbles in the liquid. The volume fraction due to helium voids in the core region under these assumptions is about 15% [A2].

As described in Section B4 the method used to simulate helium voids in the test was to introduce helium saturated water into the loop from a separate tank which was pressurized with helium at 200 psig. The test was begun (coastdown initiated) after sufficient helium containing water was introduced to displace the helium free water originally present in the test loop. When the concept of introducing the water from a separate tank was originally proposed it was not clear how well it would work since it was possible that the gas bubbles would coalesce and separate from the liquid before coastdown began. However, the concept was much simpler than the alternative of replacing the existing loop with one designed for operation at 200 psig and was considered to be worth the modest additional cost in time and money. Fortunately the experimental approach was found capable of producing void fractions of about 10% which permitted projections to be made of the effect of a void fraction of 15% that was calculated for the reactor.

D. DISCUSSION OF TEST DATA FOR SELECTED TESTS

Test 1 - Safe Flow Reversal, Single-Sided Heating

For the test conducted under the baseline conditions, the maximum power level for safe flow reversal is 7 KW. The 40 second flow coastdown is evident in Fig. A7.1 which shows the measured loop (pump) flow rate. The flow rate indicates that coastdown begins at about 12 seconds.

The plate temperatures at the top and bottom of the heated section are shown in Figures A7.2 and A7.3, respectively. The initial rise in wall temperature is a result of flow reduction due to pump coastdown. Initially the top wall temperature is lower than the bottom wall temperature because the forced flow is in the downward direction. At about 46 sec. the bottom wall temperature starts to decrease while the top temperature shows a more rapid rate of increase. This is an indication of flow reversal with water from the reflector region feeding the heated section from below and hot water rising up to the top of the heated section.

The top wall temperature increases to $\approx 230^{\circ}\text{F}$ and remains relatively steady for the rest of the test.

The occurrence of flow reversal is also quite obvious in the temperature response of the coolant flowing in the test section. Coolant temperatures at different locations of the test loop are shown in Figure A7.4. Flow reversal is clearly demonstrated by the increase and then stabilization of the water temperature in the channel top (inlet tube section).

The increase in wall temperature that accompanies the change from forced convection to free convection heat removal causes an increase in the electrical resistance of the heated plate. Since the electrical current was kept constant at ≈ 3 kA during the test, the increase in resistance was reflected in an upward drift in voltage across the heated section. The increase in power caused by the upward drift in voltage is shown in Figure A7.5. By the time of flow reversal, the channel power has increased from an initial value of 7 KW to 7.4 KW. The test was terminated by a manual power trip at about 170 seconds.

Bi-directional turbine flow meters were used to measure the water volumetric flow rate in the bypass and reflector region of the test loop. The measured bypass flow is shown in Figure A7.6 and the reflector flow is shown in Figure A7.7. The bypass flow reaches a local minimum at 46 sec, the time of flow reversal. Since the forced flow is still non-zero at 46 sec., the bypass flow is now a combination of forced flow and natural circulation flow until the pump completely stops at 52 sec. The initial positive flow direction of the reflector flow is away from the heated section. The first change in flow direction occurs at 46 sec. and from that point onward, the reflector flow fluctuates between a positive and negative direction. Based on visual observations, the flow oscillations after flow reversal have a period of about one to two seconds. The turbine flow meter may not have accurately followed the frequent acceleration and deceleration of the coolant flow that is associated with phase changes due to boiling and condensation. The consequence is that the bi-directional turbine flow meter may not provide accurate measurements during rapid flow transients. In Figure A7.7, there appears to be a dead band in the flowmeter for flow rates between plus and minus 0.25 gpm. The anomaly is due to the fact that the calibration constants for the turbine flowmeter are valid only for flows above 0.2 gpm in either direction. The application of the same constants for flows below 0.2 gpm then results in questionable readings.

Another parameter of interest is the channel pressure drop which provides indications of flow direction and voiding in the heated section. Five differential pressure transducers were used to measure the pressure drop due to friction and acceleration along the heated section. Figure A7.8 shows the overall channel pressure drop (sum of the pressure drop in each quarter of the heated

section).

Mathematically the measured channel pressure drop represents,

$$\Delta P_{\text{Channel}} = P_{\text{Top}} - P_{\text{Bottom}} + H_L$$

where

P_{Top} = Static pressure at the top of the heated section.

P_{Bottom} = Static pressure at the bottom of the heated section.

H_L = Hydrostatic pressure of stagnant water equivalent to the height of the heated section.

When water is stagnant in the heated section, $\Delta P_{\text{Channel}} = 0$. Channel pressure drop is positive ($\Delta P_{\text{Channel}} > 0$) for single-phase liquid downflow and negative ($\Delta P_{\text{Channel}} < 0$) for single-phase liquid upflow. Any voiding in the channel will have a positive contribution to the channel pressure drop. In Figure A7.8 the channel pressure drop is seen to decrease during the flow coastdown and then rise rapidly at the time of flow reversal. The increase in measured pressure drop is due to voiding in the channel. A completely voided channel with zero flow would have reached a pressure drop reading of ≈ 0.9 psi.

The data from the baseline test at 7 KW demonstrated that natural circulation was established in the coolant channel after flow reversal and there was no overheating of the heated plates during and after the reversal.

Test 2 - Power Trip, Single-Side Heating

A wall temperature trip was the result of conducting the baseline test at an initial power level of 7.5 KW. The trip occurred a few seconds after the first change in flow direction was recorded while there was still forced downflow from the pump.

The pump flow data shown in Figure A8.1 indicates that the 40 sec. flow coastdown starts at about 26 sec.

In Figure A8.2 the temperature response of the heated plate at the top of the test section shows a spike at about 52 sec. The first temperature spike lasts about 2 seconds followed by another rapid rise that hits the trip setpoint at about 57 seconds. Depending on the power level, all plate temperature trips were set at a temperature of 30 - 40 degrees above the test section exit saturation temperature. Typical trip setpoint was between 260°F and 280°F. The plate temperature at the bottom of the heated section, shown in Figure A8.3, never reaches the saturation temperature of $\approx 230^\circ\text{F}$ during the whole transient. The two dips in temperature after 52 seconds tend to suggest that some water did enter the test

section briefly from below.

In this flow transient, the reversal has started but was not yet established by the time of the power trip. This observation can be deduced from the coolant temperature data shown in Figure A8.4. The temperature of the coolant just above the top of the heated section is increasing after 52 seconds but it reaches only 180°F by the time of the trip, still 50 degrees F below the saturation temperature.

The voltage and power data shown in Figure A8.5 do not exhibit any rapid change prior to the power trip.

The behavior of the bypass flow, shown in Figure A8.6, and the reflector flow, shown in Figure A8.7, at the time of flow reversal is typical of all flow reversal tests. At the time of flow reversal, there is an increase in the bypass flow and a change in flow direction of the reflector flow.

The channel pressure drop shown in Figure A8.8 reaches a peak value of 0.6 psi when the power trip occurred. The peak pressure drop for the corresponding safe flow reversal case is 0.5 psi (see Figure A1.8). Figure A8.8 shows that the overall channel pressure drop is above 0.5 psi for about 2 seconds right before the power trip. Assuming negligible pressure drop due to coolant flow, a 0.5 psi pressure drop is equivalent to about 60% ($0.5/0.9$) void fraction in the heated section. The data tend to support a correlation between the power trip and the channel void fraction being above a threshold value for a short period of time.

References:

- [A1] Yang, B.W., et.al, 1993, "BNL Single Channel Thermal Hydraulic Test Program for the HFBR," Columbia University Heat Transfer Research Facility, CU-HTRF-93-05 (Final Report, Vol. I and II).
- [A2] Tichler, P.R., 1989, "Effect of Helium Dissolution on Core Heat Transfer Following Emergency Shutdown," BNL Memorandum to Files.
- [A3] Yang, B.W., et.al., 1994, "Helium Evolution and Bypass Flow Restriction Effects," CU-HTRF-94-02 (Final Report - Vol. I and II).
- [A4] Yang, B.W., et.al., 1995, "Flow Reversal with Reduced Bypass Flow Restriction," CU-HTRF-95-03 (Final Report - Vol. I and II).
- [A5] Ishii, M. and Kataoka, I., 1984, "Scaling Laws for Thermal Hydraulic System Under Single-Phase and Two-Phase Natural Circulation," Nuclear Engineering Design, Vol. 81, pp 411-425.
- [A6] Cheng, L.Y., 1992, "Scaling Criteria for the Single-Channel Test," BNL Memorandum to Files.
- [A7] Tichler, P., 1995, "Power Density Ratio in Hot Stripe of Hot Plate Under Shutdown Conditions," BNL Memorandum to Files.
- [A8] Mevs, Ralph, 1991, "Primary Pump and Pony Motor Coastdown Flow Measurement," BNL Memorandum.
- [A9] Tichler, P.R., Cheng, L.Y., and Fauske, H., 1991, "Core Cooling Under Accident Conditions at the High Flux Beam Reactor (HFBR)," Transactions ANS, Vol. 64, pp. 385-386.
- [A10] Monde, M., Kusuda, H., and Uehara, H., 1982, "Critical Heat Flux during Natural Convective Boiling in Vertical Rectangular Channels Submerged in Saturated Liquid," J. Heat Transfer, 104, pp. 300-303.
- [A11] Mishima, K. and Nishihara, H., 1982, "The Effect of Flow Direction and Magnitude on CHF for Low Pressure Water in Thin Rectangular Channels," Nuc. Eng. & Design, 86, pp. 165-181.

LIST OF TABLES

- A1 Heated Section Dimensions.
- A2 Instrumentation for the Test Loops.

LIST OF FIGURES

- A1 Schematic of the Flow Reversal Test Loop.
- A2 Cross-Section of the Single Heater Test Section.
- A3 Schematic of Test Loop for First Test Series.
- A4 Schematic of Test Loop for Helium Tests.
- A5 Schematic of Test Loop for Extended Bypass Ratio Tests.
- A6 Stages of the Flow Reversal Process.
- A7.1 - A7.8
Test Data for Test No. B080394B.
- A8.1 - A8.8
Test Data for Test No. B080394A.

TABLE A1

HEATED SECTION DIMENSIONS

<u>Single Sided Heater</u>	
width of channel	2.160 inches
channel gap	0.10 - 0.113 inches
channel length	24.00 inches
heater width	2.25 inches
heater length	22.750 inches
heater thickness	0.050 inches
<u>Double Sided Heater</u>	
width of channel	2.160 inches
channel gap	0.098 - 0.116 inches
channel length	24.00 inches
heater width	2.25 inches
heater length	22.750 inches
thickness of heaters	0.025 inches

TABLE A2		
<u>INSTRUMENTATION FOR THE TEST LOOPS</u>		
NAME	INSTRUMENT	DESCRIPTION
FLI1	Turbine flowmeter	Loop (pump) volumetric flow rate.
FBP	Bi-directional turbine flowmeter	Bypass volumetric flow rate.
FRE	Bi-directional turbine flowmeter	Reflector (channel) volumetric flow rate.
FBP2	Turbine flowmeter	Flow in secondary bypass (see Figure A5).
DO1	Differential pressure transducer	Pressure drop across orifice plate in the bypass line.
DRE	Differential pressure transducer	Pressure drop across turbine flowmeter in the reflector section.
RTP1	RTD	Coolant temperature in the upper plenum.
RTI1/ JTI1	RTD/thermocouple	Coolant temperature in the inlet section (channel top)
RT01/ JT01	RTD/Thermocouple	Coolant temperature in region below the heated section .
JT02	Thermocouple	Coolant temperature in region immediately below heated section (see Figure A5).
RTR1	RTD	Coolant temperature in the reflector section.
JRP1	Thermocouple	Coolant temperature in the bypass section.
JRB1	Thermocouple	Coolant temperature upstream of the heat exchanger (H.E.).
EW01- EW09	Thermocouple	Wall temperature of single-sided heater.
EW101- EW109	Thermocouple	Wall temperature of first plate in the two-sided heater.

TABLE A2

INSTRUMENTATION FOR THE TEST LOOPS

NAME	INSTRUMENT	DESCRIPTION
EW201- EW209	Thermocouple	Wall temperature of second plate in the two-sided heater.
DT1-DT4	Differential pressure transducer	Pressure drop (friction and acceleration) in each quarter of the heated section.
DT5	Differential pressure transducer	Overall pressure drop (friction and acceleration) in the heated section.
DP	Differential pressure transducer	Pressure drop in upper plenum (for estimating void fraction, see Figure A4).
PTP1	Absolute pressure transmitter	Pressure in the upper plenum.
PTIB	Absolute pressure transmitter	Pressure in the inlet section.
PTOB	Absolute pressure transmitter	Pressure in region below the heated section.
P1-P5	Absolute pressure transducer	Pressure in heated section (see Figure A5).
Vts	Voltage	Voltage across heated section.
Its	Current	Current in heated section.

ITEM NO.	QTY.	DESCRIPTION
1	-	PLEXIGLAS
2	-	SIDE RAIL (ASBESTOS PHENOLIC)
3	-	KAPTON TAPE (4 LAYERS)
4	-	ALUMINUM HEATER STRIP (WIDTH = 2.25)
5	-	INSULATOR (PEEK)

NOTE:

1. ALL DIMENSIONS ARE NOMINAL VALUES AND IN INCHES.

Figure A2

Cross-Section of the Single-Heater Test Section

Figure A3

COLUMBIA UNIVERSITY HEAT TRANSFER RESEARCH FACILITY 632 W 125 STREET N.Y. N.Y. 10027			
DRAWN	A.K.	DATE	7/31/95
CHECKED		DATE	
APPROVED		DATE	
SIZE	B	DRAWING NUMBER	BNL95PR8
ISSUE	A		

PRINT DATE: 8-24-95
 DIR:BNL95\BNL95PR8

Figure A5

Figure A6
Stages of the Flow Reversal Process

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T inlet = 130 °F Coast Down = 40 Sec
Orifice ID=0.199"

Figure A7.1

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.2

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.3

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.4

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.5

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.6

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.7

BNL TEST B080394B (FLOW REVERSAL)
Nominal Power = 7.0 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A7.8

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
Orifice ID=0.199"

Figure A8.1

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A8.2

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A8.3

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure 8.4

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
Orifice ID=0.199"

Figure A8.5

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
Orifice ID=0.199"

Time (Sec)
Figure A8.6

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A8.7

BNL TEST B080394A (FLOW REVERSAL)
Nominal Power = 7.5 KW T Inlet = 130 °F Coast Down = 40 Sec
TS:BP Ratio=2:1 (Orifice ID=0.199")

Figure A8.8

THIS PAGE IS BLANK

APPENDIX B

RELAP5 MODEL AND COMPARISON WITH TEST RESULTS

A. MODEL DESCRIPTION

A RELAP5 model has been developed [B1] to simulate the flow reversal tests conducted at Columbia University. The results of the numerical simulations are used to develop an analytical success criterion for safe flow reversal. The success criterion is represented by a time-averaged channel void fraction. The value of the critical void fraction is established by comparing the RELAP5 calculation with the outcome of the corresponding flow reversal test.

RELAP5 [B2] is a system thermal-hydraulic code developed at the Idaho National Engineering Laboratory (INEL) for the analysis of power reactors. Recent updates to RELAP5 has made the code more applicable to DOE research reactors [B3]. The version of RELAP5 used in the simulation of the flow reversal tests is mod 3.1.1.1 released to BNL by INEL in July 1994. During the development of the RELAP5 model for the flow reversal tests, it was observed that high steam condensation rates were calculated at the steam-water interface resulting in unrealistic simulation of the tests. The interfacial heat transfer coefficient on the liquid side was modified [B4] to reflect the conditions observed during the actual tests. In effect, the coefficients were reduced for the bubbly subcooled liquid and the slug subcooled liquid flow regimes.

The scope of the test program had been expanded twice since the first successful test conducted in February 1993. The test loop had been modified accordingly to accommodate the new test conditions. A RELAP5 representation of the test loop is shown in Figure B1. The original RELAP5 model [B1] has since been modified to reflect the three test loop configurations used in the flow reversal tests. Details of the model changes are discussed in Ref. B5.

The RELAP5 calculations were set up to reflect the test conditions. Generally they were done in pairs, one representing safe flow reversal and the other at a slightly higher power level representing the tripped case. The principal variants of the tests were:

1. Power to the Heated Section

The aluminum plate(s) that form the channel wall(s) was directly heated by DC power. There was an upward power drift as the plate temperatures increased during flow coastdown and flow reversal. The reference power for the safe cases was the measured power at the time of flow reversal. For the tripped cases, the reference power was the power just before the trip. Heat loss from the heated section was estimated at 4% and 5%

for the cases of single heater and double heater respectively. The actual power used in the calculation was 96% and 95% of the reference power for the safe and tripped cases respectively. The aluminum plates were assumed uniformly heated and the power were kept constant for each calculation. Each aluminum plate and the adjacent coolant channel were divided into 16 axial nodes.

2. Pump Coastdown

In the flow reversal tests, the pump was programmed to provide a linear flow coastdown. The nominal coastdown time from 3 gpm to zero flow was set at 40 seconds. Other coastdown times tested were 30 seconds and 60 seconds. Tripping the circulating pump resulted in an equivalent coastdown time of 1.5 seconds. Time dependent junctions were used in the RELAP5 calculations to represent the flows to and from the circulating pump. At any given time during the simulated coastdown, the suction flow was equal to the injection flow.

3. Initial Coolant Temperature

The initial coolant temperature of 130°F was maintained in the flow reversal test by passing the coolant through a heat exchanger located upstream of the pump. Two other coolant temperatures were used in the test, 110°F and 150°F. In RELAP5, the coolant temperature was specified in the time dependent volume that supplied flow to the time dependent junction representing the pump injection flow.

4. Initial Water Level

The normal water level in the HFBR is 14' above the transition plate. The water level was set nominally at 14' above the inlet tube section of the test loop. A lower water level of 3.67' was also tested. The test loop did not have a pressurized cover gas region as in the HFBR. The upper plenum region of the test loop actually opened to the atmosphere. In RELAP5, the initial water level was set by specifying a saturated steam condition in the hydrodynamic volumes above the free surface. A time dependent volume with saturated steam at atmospheric pressure was used to represent the ambient pressure condition above the upper plenum region of the test loop. The use of steam instead of air in the gaseous space above the water level was to avoid any unexpected complications resulting from including a non-condensable gas in a RELAP5 calculation. The heat and mass transfer across the steam/water free surface had negligible effect on the calculations because of the column of subcooled water between the heated section and the free surface.

5. Bypass Ratio

The bypass section of the test loop represented the flow paths in the HFBR that are parallel to the fuel elements. In the

forced downflow situation, these parallel flow paths divert a fraction of the total flow away from the fuel elements. The difference between the total downflow and the core flow (flow through the fuel elements) is the bypass flow. The bypass flow accounts for flow through the open flow reversal valves and flows in or around reactor vessel internal structures that penetrate the transition plate. The bypass ratio is defined to be the ratio of the core flow to the bypass flow. The bypass ratio corresponding to the initial pump flow of 3 gpm in the test was determined to be 2:1 [B6]. This bypass ratio of 2:1 was realized in the test by installing a 0.199" diameter orifice in the bypass section of the test loop. A smaller orifice of 0.129" diameter was used in the test to simulate the condition of partial loss of bypass flow path, such as the failure of one of the flow reversal valves to open. The smaller orifice resulted in a bypass ratio of 5:1. In order to check the effects of a less restrictive return flow path on flow reversal, a 0.28" diameter orifice was used. This third orifice resulted in a bypass ratio of 1.5:1. The orifice plate was modeled in RELAP5 as a flow junction, using the actual orifice flow area and a user supplied loss coefficient. The loss coefficient was adjusted to achieve the proper bypass ratio for each orifice. In one series of tests a valve was used to adjust the bypass flow. For that test configuration a bypass ratio of 1:3.4 was achieved.

6. Mode of Heating

Two heated sections were used. In the single-sided heater, the coolant channel was bounded on one side by a heated plate and the other by a slab of Plexiglas. In the two-sided heater, the coolant channel was bounded on each side by a heated plate. The channel gap was slightly different for the two heated sections. There was no direct measurement of the as-installed dimension of the channel gap. The design specification allowed the gap to vary between 0.10" and 0.113" for the single-sided heater, and between 0.098" and 0.116" for the two-sided heater. The RELAP5 calculations assumed the high end of the range for the channel gap. Generally a wider gap would impose a lesser resistance to flow and that is likely to translate to a lower peak wall temperature and lower void fraction in the channel during flow reversal. It is then expected that a dryout criterion developed from calculations using a wider gap would be more conservative than the case of using a smaller gap. In RELAP5 the heated plates were represented by rectangular heat structures with uniform heat sources.

7. Dissolved Helium

In one series of flow reversal tests, water saturated with dissolved helium was circulated in the test loop prior to the initiation of a flow coastdown. The effect of helium on flow reversal was assessed experimentally but no RELAP5 calculation

was done to simulate the impact of dissolved gas.

8. Secondary Bypass

In the last series of tests a second bypass line was installed to allow for the injection of unheated water into the region below the heated section. The RELAP5 model was revised accordingly to reflect this change in the test loop.

B. COMPARISON OF RELAP5 SIMULATIONS WITH TEST RESULTS

A list of flow reversal tests that have been simulated by RELAP5 is shown in Table B1. Each RELAP5 calculation was first initialized to a steady state and the flow coastdown or pump trip was then started at a time equal to 5 seconds. The focus of the RELAP5 analysis was to characterize the thermal-hydraulic response of the heated section during a flow reversal transient. Based on the test results, the timing of flow reversal was always near the end of the flow coastdown. If there was a dryout during flow reversal it generally occurred within a few seconds after the initiation of flow reversal. For all the coastdown cases, it was then adequate to carry the calculation out to 15 seconds after the forced flow has stopped. Plots of selected variables calculated by RELAP5 for 2 test simulations are shown in Figures B2.1 through B3.11.

RELAP5 run #101 represents a case of safe flow reversal under baseline conditions. The original loop configuration was assumed for this calculation. The channel power was 7 kW. The 40 sec. coastdown was started at 5 sec. and the first change in flow direction occurred at about 36 sec. Figure B2.1 shows the mass flow rate at the top and bottom of the heated section. The positive flow direction is downward. The timings of the four stages of flow reversal are also indicated in the figure. The coastdown stage was between 5 sec. and ≈ 35 sec. The vapor generation stage was between ≈ 35 sec. and ≈ 37 sec. The generation of steam resulted in the expulsion of coolant out of the heated section. In this stage, the mass flow was out of the heated section at both top and bottom. The much lower mass flow rate at the bottom of the heated section was indicative of mostly steam flow out of the bottom. The oscillatory flow stage lasted between ≈ 37 sec. and ≈ 45 sec. During this period there were changes in the direction of the net mass flow. At times the mass flow at the top and bottom of the heated section were in opposite directions. Quasi-steady state natural circulation flow appeared to be in place for times greater than ≈ 45 sec. That was also the time when the forced flow had completely stopped.

The calculated void fraction in the heated channel was shown in Figures B2.2 to B2.5. The sixteen coolant nodes in the heated section were numbered from top to bottom in ascending order. The initiation of flow reversal basically coincided with the first appearance of steam void in the heated channel. There was a rapid

rise in void fraction throughout the whole channel during the vapor generation stage of the transient (between ≈ 35 sec. and ≈ 37 sec.) All coolant nodes experienced a maximum void fraction of 90-98%. In the oscillatory flow stage, each succeeding peak in void fraction was lower than the previous peak. The void fraction in the upper quarter of the heated section was seen to vary periodically in the natural circulation stage of the transient. The coolant flow in the lower half of the channel was single-phase liquid. Figure B2.6 is a plot of the average void fraction in the heated section. This channel void fraction represents the arithmetic mean of the void fraction in the 16 coolant nodes. The channel void fraction reached a peak value of $\approx 90\%$ in the vapor generation stage of the flow reversal transient. In the oscillatory flow stage, each oscillation cycle resulted in more liquid reaching the heated section. This was reflected in the reduction of succeeding peaks of the channel void fraction during the oscillatory flow stage. The periodic variation of the channel void fraction in the natural circulation stage of the transient was out of phase with the channel flow. A smaller flow results in more steam generation which led to a higher channel void fraction. The higher channel void fraction created a more favorable pressure potential for natural circulation flow. The subsequent increase in flow reduced the channel void fraction and also the pressure potential for natural circulation. In Figure B2.1 the natural circulation flow calculated by RELAP5 was seen to cycle through periods of increasing and decreasing flow while the corresponding channel void fraction was seen in Figure B2.6 to pass through periods of decreasing and increasing values. The results of the calculations indicate that the RELAP5 code is capable of predicting the behavior of natural circulation flow.

A period of oscillation of approximately 2 seconds has been observed from both the experimental data and the RELAP5 calculation. Each oscillation cycle can be broken down into three stages. In the heat up stage subcooled water in the coolant channel is heated up to the boiling point. In the voiding stage sufficient steam is generated to expel water from the channel. In the refilling stage the coolant channel is again filled with water. The cycle then repeats itself. The observed oscillation period of ≈ 2 sec. can be shown to be roughly equal to the time it takes to heat up the coolant in a channel to saturation. For an initial coolant temperature of T_i , the time to saturation τ_s can be estimated by,

$$\tau_s = \frac{m_{ch} C_p (T_{sat} - T_i)}{\dot{E}}$$

where

m_{ch} = mass of coolant in the heated section
 T_{sat} = saturation temperature
 C_p = specific heat capacity of the coolant
 E = channel power

At a channel power of 7 kW, the initial temperature of the reflector region is 154°F. Thus,

$$\tau_s = \frac{(0.1 \times 2.16 \times 24)}{12^3} ft^3 \times \frac{59 lbm}{ft^3} \times 1 \frac{BTU}{lbm-^{\circ}F} \times \frac{(233 - 154)^{\circ}F}{7/1.055 BTU/sec}$$

$$= 2.1 \text{ sec.}$$

The heat up time of 2.1 sec. is approximately the period of channel void oscillation shown in Figure B2.6. It is obvious from the expression for τ_s that the period will be shorter for higher channel power. The period will also be shortened by a higher temperature in the reflector region. In the course of natural circulation, the temperature of the reflector region will decrease initially due to the arrival of the cooler water from the upper plenum (nominally at 130°F). As the upper plenum heats up, the reflector region will eventually experience an increase in temperature.

The coolant temperatures as calculated by RELAP5 are shown in Figure B2.7. Flow reversal can be identified by the sudden increase in the water temperature in the inlet tube section. The initial increase in temperature in the lower plenum region during the coastdown stage of the transient was due to decreasing forced channel flow. Once the flow had reversed, coolant from the reflector region started to flow into the lower plenum region lowering its temperature. An incremental rise in temperature was also seen in the upper plenum region after flow reversal.

The calculated plate temperatures are shown in Figures B2.8 to B2.11. Each figure shows the individual average temperature of the four axial nodes in each quarter of the heated section.

All 16 nodes reached their peak temperatures during the vapor generation stage of the transient (≈ 35 sec to ≈ 37 sec). The temperature fluctuations during the oscillatory flow stage were of the order of 20 deg. F. In conjunction with flow reversal was a reversal in the axial temperature distribution of the heated plate. During the period of forced downflow, the upper nodes were at a lower temperature than the lower nodes. The reverse trend occurred in natural circulation. This was particularly obvious in the single-phase region. For example in Figure B2.11, at times greater than 45 sec., the upper nodes were at a higher temperature than the lower nodes. The calculated peak wall temperature of about 285°F (414°K) did not agree with the test data. The data showed the plate

temperature to increase to the saturation temperature of $\approx 230^{\circ}\text{F}$ during flow reversal. The first (top) thermocouple was observed to stay at the saturation temperature for the rest of the transient. The data also did not exhibit any temperature fluctuations of more than 10 deg F. In comparison with the test data, the calculated wall temperatures were generally higher than the measured values and fluctuations in the calculated wall temperature were of greater magnitude than the observed values.

The companion case to RELAP5 run #101 is run #102. RELAP5 run #102 represents a case of dryout during flow reversal under baseline conditions. These two RELAP5 runs correspond to the pair of flow reversal tests which bracketed the dryout power for the baseline conditions. The channel power was 7.6 kW and it corresponded to the power level at the time of trip (minus 4% for heat loss). The results of this calculation are similar to those of run #101. The calculated mass flow at the top and bottom of the heated section are shown in Figure B3.1. The local void fractions are shown in Figures B3.2 to B3.5. The channel void fraction is shown in Figure B3.6. Here a distinction between the safe case and the tripped case is noted. In the dryout case, the channel void fraction did not decay as fast as in the safe case. Qualitatively, the RELAP5 calculation indicated that during the oscillatory flow stage the channel void fraction was higher for the dryout case than for the safe flow reversal case. The calculated coolant temperatures are shown in Figure B3.7. The plate temperatures are shown in Figures B3.8 to B3.11. They are generally slightly higher than the corresponding temperatures for run #101, the safe case.

In summary, the RELAP5 simulations of the flow reversal tests are found to reproduce the general aspects of the observed behavior of the tests. These include the timing of the onset of flow reversal, the period of flow and void oscillations, and the extensive voiding that was observed visually prior to dryout. However, the calculated plate temperatures tend to be higher than the measured values. The heat transfer correlations in RELAP5 are based primarily on data developed for rod bundle and tube geometries and high pressure conditions applicable to power reactors. The accuracy of applying the existing heat transfer correlations to narrow channel geometry and low pressure condition has not been established. The following section summarizes the results of using channel void fraction as a dryout criterion.

C. COMPARISON OF TIME AVERAGE VOID FRACTIONS IN RELAP5 SIMULATIONS

Time averaging was performed on the RELAP5 simulation of tests that are identified in Table B1. The maximum time averaged void fraction for each of the test simulations is displayed in this table. The instantaneous and time averaged channel void fractions are shown in Figures B4.1 through B4.31 for each test simulation.

These tests cover a wide range of inlet temperatures, bypass ratios, and coastdown times and include both one sided and two sided heating tests. A comparison of the maximum time averaged channel void fractions for the 17 test conditions is shown in Figure B5.

References:

- [B1] Cheng, Lap Y., 1995, "A RELAP5 Model of the Flow Reversal Tests," BNL Memorandum to Files.
- [B2] Carlson, K.E., et.al., 1990, "RELAP5 Mod 3 Code Manual Volume I: Code Structure, System Models, and Solution Methods," NUREG/CR-5535 (Draft).
- [B3] RELAP5 3.1.1 Input Manual, transmitted to BNL from Nancy Larson of INEL via letter number nsl-148-93.
- [B4] Cheng, Lap Y., 1995, "Modifications to Interfacial Heat Transfer Coefficient in RELAP5," BNL Memorandum to Files.
- [B5] Cheng, Lap Y., 1995, "RELAP5 Inputs for Analyzing Flow Reversal Tests," BNL Memorandum to Files.
- [B6] Cheng, Lap Y., 1991, "Fraction of Bypass Flow and Pressure Loss in the Single-Channel Test," BNL Memorandum to Files.

LIST OF TABLE

B1 List of RELAP5 Simulations of Flow Reversal Tests.

LIST OF FIGURES

B1 RELAP5 Representation of the Flow Reversal Tests.

B2.1 - B2.11
Plots for RELAP5 Run #101.

B3.1 - B3.11
Plots for RELAP5 Run #102.

B4.1 - B4.31
Instantaneous and Time-Averaged Channel Void Fraction
for RELAP5 Runs Listed in Table B1.

B5 Comparison of Maximum Time-Averaged Channel Void Fraction
Calculated for Different Test Conditions.

TABLE B1

LIST OF RELAP5 SIMULATIONS OF FLOW REVERSAL TESTS

RELAP5 RUN NO.	REFERENCE' TEST NO.	TEST' OUTCOME	CHANNEL+ POWER (kW)	ORIFICE'' DIAMETER (in.)	BYPASS'' RATIO	NUMBER SIDES HEATED	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	MAXIMUM'' VOID FRACTION
101	B021393F ⁽¹⁾	FR	7.0	0.199	2:1	1	130	40	0.696
102	B021393H ⁽¹⁾	Trip	7.6	0.199	2:1	1	130	40	0.761
103	B021393J ⁽¹⁾	FR	7.6	0.199	2:1	1	130	30	0.716
104	B021393K ⁽¹⁾	Trip	8.4	0.199	2:1	1	130	30	0.789
107	B021393Q ⁽¹⁾	FR	8.3	0.199	2:1	1	110	40	0.704
108	B021393R ⁽¹⁾	Trip	9.1	0.199	2:1	1	110	40	0.771
109	B030493D ⁽¹⁾	FR	6.9	0.199	2:1	1	130	40	0.762
110	B030493E ⁽¹⁾	Trip	7.8	0.199	2:1	1	130	40	0.829
112	B080394E ⁽¹⁾	Trip	6.8	0.129	5:1	1	130	40	0.884
113	B080394D ⁽¹⁾	FR	6.4	0.129	5:1	1	130	40	0.860
114	B080394G ⁽¹⁾	FR	7.9	0.28	1.5:1	1	130	40	0.739
115	B080394H ⁽¹⁾	Trip	8.2	0.28	1.5:1	1	130	40	0.766
302	B101694B ⁽²⁾	FR	7.5	0.199	1.42:1	1	130	40	0.819
303	B101694C ⁽²⁾	Trip	8.5	0.199	1.42:1	1	130	40	0.904
304	B101694F ⁽²⁾	Trip	7.4	0.199	1.42:1	1	130	60	0.851
305	B101694G ⁽²⁾	FR	6.7	0.199	1.42:1	1	130	60	0.777
306	B101694K ⁽²⁾	Trip	6.9	0.129	2.78:1	1	130	40	0.895
307	B101694L ⁽²⁾	FR	6.7	0.129	2.78:1	1	130	40	0.894

TABLE B1 (CONTINUED)

LIST OF RELAP5 SIMULATIONS OF FLOW REVERSAL TESTS

RELAP5 RUN NO.	REFERENCE* TEST NO.	TEST* OUTCOME	CHANNEL* POWER (kW)	ORIFICE** DIAMETER (in.)	BYPASS** RATIO	NUMBER SIDES HEATED	INLET TEMP. (°F)	COASTDOWN TIME (sec.)	MAXIMUM** VOID FRACTION
201	B061293E ⁽¹⁾	FR	8.3	0.199	2:1	2	130	40	0.784
202	B061293G ⁽¹⁾	Trip	8.9	0.199	2:1	2	130	40	0.819
204	B061293I ⁽¹⁾	Trip	7.3	0.199	2:1	2	150	40	0.824
205	B061293J ⁽¹⁾	FR	6.4	0.199	2:1	2	150	40	0.743
206	B061293K ⁽¹⁾	Trip	7.5	0.199	2:1	2	130	60	0.775
207	B061293L ⁽¹⁾	FR	6.9	0.199	2:1	2	130	60	0.701
1	B081395E ⁽³⁾	FR	9.0	-	2:1:0	1	130	40	0.713
2	B081395F ⁽³⁾	Trip	9.8	-	2:1:0	1	130	40	0.774
10	B081395K ⁽³⁾	FR	13.8	-	1:3.4:0	1	130	40	0.860
21	B081395N ⁽³⁾	FR	13.8	-	1:3.4:0.6	1	130	40	0.668
6	B081395U ⁽³⁾	FR	11.5	-	2:1:1.2	1	125	40	0.55
5	B081395V ⁽³⁾	Trip	13.2	-	2:1:1.2	1	130	40	0.667
11	B081795C ⁽³⁾	FR	19.0	-	1:3.4:0.6	1	130	1.5	0.718

Notes:

* The number in parenthesis after the test number is the test loop configuration: (1) refers to Figure 3; (2) refers to Figure 4; (3) refers to Figure 5.

FR means a successful flow reversal without a power trip for 30 seconds after initiation of flow reversal.

+ Channel power corresponds to either the flow reversal power or the trip power given in Tables 2. The channel power listed includes a reduction of 4% and 5% to account for heat loss from the single-sided and two-sided heaters respectively.

** A numerical value indicates orifice diameter in bypass path in test configurations (1) and (2). A (-) indicates use of throttling valve in bypass path.

Refers to ratio of flow rates under initial conditions. First number applies to section flow, second number applies to primary bypass flow and third number, if present, applies to secondary bypass flow in test configuration 3.

++ Maximum time-averaged void fraction during the 10 second interval following reversal in RELAP5 calculation. The time averaging period is two seconds.

Figure B1 RELAP5 Representation of the Flow Reversal Test

Mass Flow Rate at Top and Bottom of Heated Channel
(RELAP5 Run #101)

Figure B2.1

Local Void Fraction of Nodes in First (Top) Quarter of Heated Channel
(RELAP5 Run #101)

Figure B2.2

Local Void Fraction of Nodes in Second Quarter of Heated Channel
(RELAP5 Run #101)

Figure B2.3

Local Void Fraction of Nodes in Third Quarter of Heated Channel (RELAP5 Run #101)

Figure B2.4

Local Void Fraction of Nodes in Fourth (Bottom) Quarter of Heated Channel
(RELAP5 Run #101)

Figure B2.5

Channel Average Void Fraction
(RELAP5 Run #101)

Time (s)
Figure B2.6

Water Temperatures in Test Loop (RELAP5 Run #101)

Figure B2.7

Wall Temperature of Nodes in First (Top) Quarter of Heated Plate
(RELAP5 Run #101)

Wall Temperature of Nodes in Second Quarter of Heated Plate
(RELAP5 Run #101)

Figure B2.9

Wall Temperature of Nodes in Third Quarter of Heated Plate
(RELAP5 Run #101)

Wall Temperature of Nodes in Fourth (Bottom) Quarter of Heated Plate
(RELAP5 Run #101)

Figure B2.11

Mass Flow Rate at Top and Bottom of Heated Channel
(RELAP5 Run #102)

Local Void Fraction of Nodes in First (Top) Quarter of Heated Channel
(RELAP5 Run #102)

Figure B3.2

Local Void Fraction of Nodes in Second Quarter of Heated Channel
(RELAP5 Run #102)

Figure B3.3

Local Void Fraction of Nodes in Third Quarter of Heated Channel
(RELAP5 Run #102)

Figure B3.4

Local Void Fraction of Nodes in Fourth (Bottom) Quarter of Heated Channel
(RELAP5 Run #102)

Figure B3.6

Water Temperatures in Test Loop (RELAP5 Run #102)

Wall Temperature of Nodes in First (Top) Quarter of Heated Plate
(RELAP5 Run #102)

Figure B3.8

Wall Temperature of Nodes in Second Quarter of Heated Plate
(RELAP5 Run #102)

Wall Temperature of Nodes in Third Quarter of Heated Plate
(RELAP5 Run #102)

Figure B3.10

Wall Temperature of Nodes in Fourth (Bottom) Quarter of Heated Plate
(RELAP5 Run #102)

RELAP5 Run # 101 (No Dryout) One-sided Heating

Figure B4.1

RELAP5 Run # 102 (Dryout) One-sided Heating

Figure B4.2

RELAP5 Run # 103 (No Dryout) One-sided Heating

Figure B4.3

RELAP5 Run # 104 (Dryout) One-sided Heating

Figure R4.4

RELAP5 Run # 107 (No Dryout) One-sided Heating

Figure B4.5

RELAP5 Run # 108 (Dryout) One-sided Heating

Figure B4.6

RELAP5 Run # 109 (No Dryout) One-sided Heating

Figure B4.7

RELAP5 Run # 110 (Dryout) One-sided Heating

Figure B4.8

RELAP5 Run # 112 (Dryout) One-sided Heating

Figure B4.9

RELAP5 Run # 113 (No Dryout) One-sided Heating

Figure B4.10

RELAP5 Run # 114 (No Dryout) One-sided Heating

Figure B4.11

RELAP5 Run # 115 (Dryout) One-sided Heating

Figure B4.12

RELAP5 Run # 302 (No Dryout) One-sided Heating

Figure B4.13

RELAP5 Run # 303 (Dryout) One-sided Heating

Figure B4.14

RELAP5 Run # 304 (Dryout) One-sided Heating

Figure B4.15

RELAP5 Run # 305 (No Dryout)
One-sided Heating

Figure B4.16

RELAP5 Run # 306 (Dryout) One-sided Heating

Figure B4.17

RELAP5 Run # 307 (No Dryout)
One-sided Heating

Figure B4.18

RELAP5 Run # 201 (No Dryout) Two-sided Heating

Figure B4.19

RELAP5 Run # 202 (Dryout) Two-sided Heating

RELAP5 Run # 204 (Dryout) Two-sided Heating

Figure B4.21

RELAP5 Run # 205 (No Dryout) Two-sided Heating

Figure B4.22

RELAP5 Run # 206 (Dryout) Two-sided Heating

Figure B4.23

RELAP5 Run # 207 (No Dryout) Two-sided Heating

Figure B4.24

RELAP5 Run # 1 (No Dryout) One-sided Heating

Figure B4.25

RELAP5 Run # 2 (Dryout) One-sided Heating

Figure B4.26

RELAP5 Run # 10 (No Dryout) One-sided Heating

Figure B4.27

RELAP5 Run # 21 (No Dryout) One-sided Heating

Figure B4.28

RELAP5 Run # 6 (No Dryout) One-sided Heating

Figure B4.29

RELAP5 Run # 5 (Dryout) One-sided Heating

Figure B4.30

RELAP5 Run # 11 (No Dryout) One-sided Heating

Figure B4.31

Maximum Time-Averaged (2 sec.) Channel Void Fraction

Figure B5

APPENDIX C

SIMULATION OF REACTOR ACCIDENTS WITH RELAP5

A. MODEL DESCRIPTION

The RELAP5 model of the reactor is described in detail in Reference C1. A RELAP5 node diagram of the reactor vessel and the primary loop is shown in Figure C1. Important features of the model are summarized below:

1. Core Region

- a. The 532 (28 x 19) coolant channels in the HFBR core were divided into two channel types, hot and average. The RELAP5 model of the HFBR had 3 hot channel groups and 7 average channel groups. In the hottest fuel assembly, coolant channels #2, 3 and 4 were the highest powered channels [C2]. The 3 hot channel groups in the RELAP5 model corresponded to coolant channel #2, 3 and 4 respectively. Each hot channel group was equivalent to 14 coolant channels and the total number of hot channels was 42. The remaining 490 coolant channels were divided into 7 groups of geometrically identical average channels.
- b. Fission and decay heat power were modeled as a volumetric source that was uniformly distributed in the cermet embedded in the fuel plates. Heat was then conducted through the aluminum cladding to the coolant. The heat transfer area in each lumped channel was proportional to the number of individual coolant channels represented by the lumped channel. There was a variation in the power density of the fuel plate corresponding to each lumped channel. For the base case, the axial and spanwise power distribution was assumed uniform. The effect of axial variation in power density was also examined. The time dependence of power density following reactor shutdown was modeled.
- c. For the base case calculation at a nominal 60 MW, a safety factor which accounts for normal variations and instrument uncertainties had been included. The resulting RELAP5 base case power was 64.05 MW (see Table C1). For decay power, an additional safety factor of 1.23 was included. This factor reflected an uncertainty of 11.6% in the calculation of the decay power [C3] and another 10% to account for the helium evolution effect. The 10% factor was based on the flow reversal experiments which showed that helium evolution will reduce the flow reversal power by no more than 10%. The application of this factor reflected the fact that helium evolution was

not explicitly modeled in the RELAP5 calculation.

- d. A fraction of the fission product gamma decay power (37.5%) was deposited directly in the reflector region of the reactor.

2. Other Primary System Components

- a. The 4 flow reversal valves were lumped into 1 equivalent valves.
- b. All the core bypass paths (control rod cooling, transition plate clearances, etc.) were lumped into one bypass path.
- c. The two parallel loops in the primary system, which includes the 2 pumps and heat exchangers were lumped into one equivalent loop.
- d. Shutdown pumps and pony motors were conservatively assumed not operating.
- e. Plant data were used to benchmark the primary pump model and the depressurization of the reactor via the depressurization valve HCe-102.

3. Trip Settings and Instrument Response Times

These were obtained from the 60 MW accident analysis [C2].

- a. Reactor trip will occur at a vessel water level of 209 inches with a 2.6 second delay or at a cover gas pressure of 180 psig with a 0.5 second delay.
- b. Primary pump trip will occur at a water level of 197 inches with a 2.6 second delay or at a cover gas pressure of 120 psig with a 0.5 second delay.
- c. Both the depressurization valve HCe-102 and the syphon break valve will open with a 1.5 second delay if both the water level has reached 197 inches and a pump trip has occurred.

4. Initial Conditions

The initial conditions for the RELAP5 calculation were based on combining the 60 MW design basis value [C2] with the worst case anticipated variation and instrument uncertainty. A list of the initial conditions for the base case of the RELAP5 calculations is shown in Table C1. The conditions were chosen to represent the scenario in which flow reversal will occur with minimum delay following reactor trip. This maximizes the power at the time of

flow reversal. A higher initial power, a lower primary flow rate, a lower cover gas pressure and a higher core inlet temperature all lead to an earlier flow reversal.

B. ACCIDENT SCENARIOS ANALYZED

The accidents that will lead to flow reversal were those involving a loss of forced flow cooling. Of these there were two categories of interest. One category is a loss of forced flow cooling without a loss of coolant. For this to occur in the HFBR it would be necessary to assume that the shutdown pumps and pony motors were not operating. While the shutdown pumps were not powered by a qualified power supply, the pony motors were and were currently required to be operational as a Technical Safety Requirement. However, for operational reasons it may be desirable in the future to relax this requirement. One of the accidents analyzed was therefore, a loss of forced flow cooling without loss of coolant. The accident of this type that leads to the most severe flow reversal condition (highest decay power and lowest pressure) was one involving a breach in the cover gas system. The design basis breach in the 60 MW FSAR was a circular orifice with an area of 1.39 in² and this was used in the current analysis. A break of this size, in the cover gas system results in a rapid depressurization of the reactor with a tripping of the reactor and the primary pumps within 2 seconds after breach initiation. This accident scenario was the most severe because the pump trip occurs with little delay after the reactor trip. This maximizes the decay heat at the time of flow reversal. The rapid depressurization also lowers the saturation temperature and results in flow reversal occurring at a lower pressure (atmospheric) which was another unfavorable factor. This contrasts with a depressurization due to accidental opening of depressurization valve HCe-102 which results in a relatively slow depressurization.

The other event which would lead to flow reversal was a LOCA which results in the liquid level in the reactor vessel dropping below 197 inches. Two bounding accidents of this type were examined in which the break size was the same as previously assumed. In one the break location was in a beam tube and the other was at the primary pump discharge. The latter location maximizes the leak rate because the pressure at the leak location was highest. However, in both these LOCAs, the rate of depressurization was relatively slow compared to the breach in the cover gas system, because the volumetric leak rate for a liquid was much lower than for a gas for the same hole size and pressure drop. The consequence of this was that there was a significant delay between reactor trip and pump trip. This delay results in the flow reversal occurring at a decay power that was lower than the decay power at which flow reversal occurs in the accident involving a breach in the cover gas system. In addition, at the time of flow reversal in the LOCA scenarios, the cover gas system has not fully

depressurized. This factor also results in a more favorable condition for flow reversal. Accordingly the accident involving a breach in the cover gas system was considered the bounding accident with respect to flow reversal and the discussion which follows will focus on this accident.

C. RESULTS OF ACCIDENT ANALYSIS

1. Overview

Several variations of the cover gas depressurization accident were performed using RELAP5 to determine the effect of changes in some of the input parameters. The following cases were analyzed:

a. Base Case (Case 1)

Reactor power: 64.05 MW (includes safety factor)
Fuel plate heating: assumed uniform
Flow reversal valve operating: 4
Pump coastdown: based on plant data

b. Case 2

Reactor power: 2 x base case = 128.1 MW
All other parameters are the same as base case.

c. Case 3

Reactor power: 128.1 MW
3 flow reversal valves operating, one not operating.
All other parameters are the same as the base case.

d. Case 4

Reactor power: 128.1 MW
Increase the pump friction torque coefficient by a factor of 1.5. This reduced the pump coastdown time from 57.4 to 46.2 sec. All other parameters are the same as the base case.

e. Case 5

Reactor power: 128.1 MW
Decreased the pump friction torque coefficient by a factor of 1.5. This increased the coastdown time by about 20%. All other parameters are the same as the base case.

f. Case 6

The axial power density distribution was assumed to have chopped cosine shape. All other parameters are the same

as the base case.

g. Case 7

The axial power density distribution was assumed to have an inverted chopped cosine shape. In other words the maximum power density occurs at the top and bottom of the fuel plate. All other parameters are the same as the base case.

The general characteristics of the base case results will be discussed first and will be followed by a comparison of the calculated maximum 2 second time averaged channel void fraction for the various cases.

A more detailed description of the calculations and results are given in Reference C1.

2. Base Case

The initial power for the base case was 64.05 MW and that corresponded to a nominal reactor power of 60 MW. The flow reversal transient was initiated by a breach of the reactor vessel in the cover gas region. The location of the breach was selected to result in the shortest time interval between the reactor trip and the primary pump trip. Both the reactor trip and the primary pump trip were activated by the low pressure trip setpoints for the cover gas. Figure C2.1 shows the rapid depressurization of the cover gas following the break initiation at time zero. The reactor was depressurized to the ambient pressure at 14.3 sec. The condition of zero cover gas pressure was similar to the single channel flow reversal test which had the upper plenum region opened to the atmosphere.

The primary pump coastdown began in less than one second after the reactor trip. Figure C2.2 shows the angular velocity of the primary pump as a function of time. Coastdown from initial operating speed to zero speed took about 55 seconds. The corresponding primary flow in units of gpm was shown in Figure C2.3.

The junction mass flow rates at the top and bottom of the heated section of the three hot channel groups are shown in Figures C2.4 and C2.5 respectively. In these figures the positive flow direction was downward. The first flow reversal in the three hot channel groups occurred at about the same time (≈ 47 sec. after reactor trip). Among the three hot channel groups, the first to go through flow reversal was group number 3 which had the lowest power of the hot channels but the narrowest channel gap (0.095 inches).

The junction flow rates for the 7 average channels are shown in Figures C2.6 through C2.9. For the average channel groups, it

was the highest powered group (group number 7) that first went through flow reversal.

Flows through the flow reversal valve and the core bypass flow path are shown in Figures C2.10 and C2.11 respectively. The flow reversal valve started to open at about 9 sec. (see Figure C2.12) and it stayed open for the rest of the transient. The check valve in the primary loop was partially open till the end of the flow coastdown. In Figure C2.13, the check valve was seen to remain almost fully closed after the primary pump had stopped at 57 sec.

The oscillatory behavior of the coolant channel mass flow rates shown in Figures C2.4 through C2.9 is somewhat similar to the results of the RELAP5 calculations done for the single channel test (see Appendix A). One of the major differences between the reactor and the test is the presence of multiple natural circulation flow paths in the reactor. The effect of multiple heated channels on natural circulation is that at any given time the flow direction does not have to be the same in all flow channels. This aspect of multi-channel effect is shown clearly by the individual channel mass flow rate which oscillates between upflow and downflow. The average behavior of the natural circulation flow through the HFBR core can be characterized by the time averaged flow rate in the flow paths which constitute the natural circulation loop. In the following calculation the flow through the core region is represented by the mass flow rates at the lower end of the heated channels (see Figures C2.5, C2.8 and C2.9). The flow rates are time averaged between 50 and 100 seconds.

Flow Path	Time Averaged Mass Flow Rate (kg/s)
Hot channel #1	-0.69
Hot channel #2	-0.63
Hot channel #3	-0.51
Average channel #1	2.3
Average channel #2	2.2
Average channel #3	-0.51
Average channel #4	-0.69
Average channel #5	-1.9
Average channel #6	-2.4
Average channel #7	-2.7
Core bypass	2.5
Flow reversal valve	2.9

Σ upflow channels = 10. kg/sec.

Σ downflow channels = 4.5 kg/sec.

The time averaged mass flow rates show that the upflows were balanced roughly by the downflows (i.e., downflow channels + core bypass + flow reversal valve) as to be expected for a situation of closed loop natural circulation. Another observation to be made from the above tabulation is that the magnitude of upflows is

proportional to flow area and channel power.

The state of the coolant in the flow channel is reflected by the average channel void fraction which is shown in Figures C2.14 through C2.16 for the ten channel groups. The periodic behavior of the channel void fraction can be characterized by two stages, a boiling stage and a heat up stage. When the coolant reached the boiling condition, the generation of steam voids in a channel resulted in a rapid increase in the channel void fraction. Flow began to enter the channel because of the density difference between the coolant channel and the reflector region. The coolant quickly condensed or displaced the steam in the channel and cooled down the heated wall. When the channel was occupied by single-phase liquid, the mass flow was reduced and the coolant in the channel began to heat up to boiling again. The flow in the heated channel was seen to alternate between two-phase and single-phase conditions depending on the thermal state of the coolant. The local void fraction in the 16 nodes representing the heated section of hot channel group #1 is shown in Figures C2.17 through C2.20.

The 2-second time average channel void fractions for the hot and average channels are shown in Figures C3.1 through C3.10. The maximum time-averaged (2 sec.) channel void fraction calculated for the base case is less than 0.31. The corresponding decay power used in the base case for the highest powered coolant channel in the HFBR was 7.8 kW at the time of flow reversal (see Figure C4). This channel power is in the range of the power levels tested in the flow reversal experiments. It should also be noted that the safe flow reversal power was higher for shorter coastdown times and was in excess of 19 kW for a very rapid coastdown (pump trip).

These considerations and the relatively low void fractions calculated for the HFBR core indicate that flow reversal in the multiple, parallel channel HFBR core occurs under conditions which were closer to a pump trip rather than a long coastdown.

In the case of the HFBR with variable heating rates in the channels, flow reversal does not occur simultaneously in all channels. With some of the channels in upflow while others in downflow, the coolant from the downflow channels becomes an extra source for feeding the upflow channels. This extra source supplements the core bypass flow and the flow through the flow reversal valves. In effect the existence of downflow channels is equivalent to an increase in the bypass orifice used in the single-channel flow reversal test. The apparent increase in the bypass flow area in the HFBR is the principal cause of a lower channel void fraction for the reactor than the single-channel test.

Based on the mass flow rates calculated by RELAP5 for the 10 channel groups of the HFBR core, an estimate of the ratio of channel flow to bypass flow is made with respect to the first flow reversal. From Figures C2.5 and C2.9, hot channel group #3 is seen

first to go through flow reversal at about 48 sec. Within a couple of seconds, hot channel groups nos. 1, and 3, and average channel groups nos. 6, and 7 also go through flow reversal. Thus the number of coolant channels involved in the first flow reversal is,

$$3 \times 14 \text{ (3 hot groups with 14 coolant channels per group)} + \\ 2 \times 70 \text{ (2 average groups with 70 coolant channels per group)} = 182$$

The remaining coolant channels are still in downflow and their number is 350 (532-182). In addition, the core bypass flow and the flow through the reversal valves also contribute to the total downflow. Nominally, these two flow streams amount to half of the total core flow and can be viewed as 266 (532/2) coolant channels. Therefore, the ratio of channel flow to bypass flow at the time of first flow reversal is equivalent to,

$$\frac{\text{total upflow channels}}{\text{total downflow channels}} = \frac{182}{350 + 266} = \frac{1}{3.4}$$

With each channel flow reversal there is an incremental change in the net buoyancy head generated in the core region. The increased buoyancy head tends to speed up the coastdown of the primary flow. This is similar to the case of a pump trip in the single channel flow reversal test. A rapid flow coastdown results in minimal opposition from the forced downflow to flow reversal. The rapid flow coastdown associated with flow reversal in the HFBR is seen in Figure C2.3 which shows the rapid drop in primary flow at the time of first flow reversal as calculated by RELAP5.

An indication of the propensity toward safe flow reversal is the maximum time-averaged channel void fraction at the time of reversal. A lower maximum channel void fraction means the required buoyancy head to induce a flow reversal is lower. The above discussion of the multi-channel effect is consistent with the calculated channel void fraction being lower in a multi-channel configuration (HFBR) and higher in a single channel (flow reversal test) all other conditions being equal.

3. Sensitivity Study

a. Non-uniform axial power distribution (Cases 6 and 7)

The power density variations that exist within each plate were not accounted for in the base case calculation. The axial power density shape is a function of time in the operating cycle and varies from plate to plate at a given cycle time. To address this issue an axial flux shape

which was close to the shape in a peripheral fuel element in a freshly fueled core was selected for Case 6. All the plates in the core had the same normalized shape. In this shape the peak power density occurs at the midplane and the power density is lowest at the top and bottom. For Case 7 the shape was inverted so that the maximum power density occurred at the top and bottom and the midplane has the lowest value. The normalized power densities are shown below for 8 of the 16 axial nodes used in the calculation:

<u>Node</u>	<u>Case 6</u>	<u>Case 7</u>
1	0.4659	1.3666
2	0.5794	1.2866
3	0.8110	1.2608
4	1.0378	1.1920
5	1.1920	1.0378
6	1.2608	0.8110
7	1.2866	0.5794
8	1.3666	0.4659

The axial nodes are numbered in ascending order from top to bottom. Nodes 9 to 16 are mirror images of Nodes 1 through 8.

The time-averaged channel void fractions for Cases 6 and 7 are shown in Figures C5.1 through C5.10 and C6.1 through C6.10 respectively. There were differences in the channel void fraction between the cases of uniform and non-uniform axial power distribution. However, in all the channel groups regardless of the axial power shape, the maximum time-averaged channel void fraction is in the range of 0.25 and 0.31. The maximum time averaged channel void fraction is thus not sensitive to the axial power shape in the core. Hence it is justifiable to use a uniform axial power distribution in RELAP5 calculations to determine the maximum time-averaged channel void fraction.

b. Effect of Doubling Reactor Power (Case 2)

The base case calculation indicates that flow reversal will be successful in the HFBR because the maximum time-averaged channel void fraction for the coolant channels is below the critical void fraction of 0.54. In order to establish the margin to dryout during flow reversal, the channel power needs to be increased to a level such that the maximum time-averaged channel void fraction approaches the critical void fraction. Another RELAP5 calculation was done with the reactor power and the decay power increased by a factor of two over the base case

value. The time-averaged channel void fractions for this sensitivity case are shown in Figures C7.1 through C7.10. A comparison with the result of the base case shows that, for the case of a higher channel power, the time to flow reversal from pump trip is shortened and the maximum time-averaged channel void fraction is increased to 0.5. For this higher power case, the initial reactor power is 128.1 MW and the multiplier applied to the decay power is 1.2276 (1.116×1.1). Including the multiplier, the decay power used in the calculation is equivalent to a reactor power of 157.26 MW. Even at this elevated power, the maximum time-averaged channel void fraction is still less than the critical void fraction.

c. Effect of One Closed Flow Reversal Valve (Case 3)

A variation of the accident scenario is the failure of one of the four flow reversal valves to open. With one valve remaining closed, there is a reduction in the area available to the coolant flow that bypasses the core. The previous RELAP5 calculation (Case 2) was redone with one flow reversal valve closed. The time-averaged channel void fractions for the three hot channels and the highest powered average channel are shown in Figures C8.1 through C8.4. As compared to Case 2, the time of flow reversal is delayed slightly in Case 3. This is because of a slight increase in the channel flow when the effective bypass flow area is reduced. The maximum time-averaged channel void fraction during flow reversal is slightly lower for Case 3 than Case 2, (0.47 verses 0.50). Thus the failure of one of the flow reversal valves to open has negligible effect on the maximum time-averaged void fraction.

d. Effect of a Shorter Coastdown (Case 4)

The simulation of a shorter primary pump coastdown was done by increasing the pump friction torque coefficient used in RELAP5 by a factor of 1.5. The same reactor power as in Case 2 (128.1 MW) was used for this case of a shorter coastdown. The pump speed became zero at 46.3 sec. as compared to 57.4 sec. in Case 2. The channel averaged void fractions for the three hot channels and the highest powered average channel are shown in Figures 20.1 through 20.4. It is noted that a shorter coastdown results in an earlier flow reversal and thus a higher corresponding channel power at flow reversal. However, the negative effect on flow reversal from the forced downflow is mitigated by a faster flow coastdown. According to the RELAP5 results shown in Figures C9.1 through C9.4, the comparison of the time-averaged channel void fraction between Case 2 and Case 4 is mixed. While

some of the channels are showing a higher channel void fraction for a shorter coastdown, there were other channels showing a lower channel void fraction. The net effect of an approximately 20% reduction in the coastdown time on the maximum time-averaged channel void fraction is shown to be negligible. The maximum void fraction remains unchanged at 0.5 (see Figure C9.2).

e. Effect of a Longer Coastdown (Case 5)

A longer coastdown was simulated by reducing the pump friction torque coefficient by a factor of 1.5. For the same reactor power as in Case 2 (128.1 MW), the time of zero pump speed was delayed to ≈ 67.4 sec. (the calculation ended at 60 sec. and the time of zero pump speed was obtained by extrapolation from the pump speed at 60 sec.). The time-averaged channel void fractions for the three hot channels and the highest powered average channel are shown in Figures C10.1 through C10.4. The net effect of an approximately 20% increase in the coastdown time on the maximum time-averaged channel void fraction is negligible. The maximum void again remains unchanged at 0.5 (see Figure C10.4).

References:

- [C1] Cheng, Lap Y., 1995, "Flow Reversal Limited Operating Power for the HFBR," BNL Reactor Division Calculation No. SEG-57-0.
- [C2] Tichler, P., 1982, "Addendum to the HFBR FSAR for 60 MW Operation," BNL Report.
- [C3] Tichler, P., 1989, "Decay Heating in HFBR Hot Channels," BNL Memorandum to Files.

LIST OF TABLE

- C1 Initial Conditions for the Base Case of the RELAP5 Calculations of the HFBR.

LIST OF FIGURES

- C1 RELAP5 Node Diagram of the HFBR Vessel and Primary Loop.
- C2.1 - C2.20
Plots for the Base Case of the Accident Analysis.
- C3.1 - C3.10
Time-Averaged Channel Void Fraction (Ten Channel Groups) for the Base Case (Case 1)
- C4 Decay Power in the Highest Powered Channel as a Function of Time After Shutdown.
- C5.1 - C5.10
Time-Averaged Channel Void Fraction (Ten Channel Groups) for Case 6.
- C6.1 - C6.10
Time-Averaged Channel Void Fraction (Ten Channel Groups) for Case 7.
- C7.1 - C7.10
Time-Averaged Channel Void Fraction (Ten Channel Groups) for Case 2.
- C8.1 - C8.4
Time-Averaged Channel Void Fraction (3 Hot Channel Groups and Average Channel Group #7) for Case 3.
- C9.1 - C9.4
Time-Averaged Channel Void Fraction (3 Hot Channel Groups and Average Channel Group #7) for Case 4.
- C10.1 - C10.4
Time-Averaged Channel Void Fraction (3 Hot Channel Groups and Average Channel Group #7) for Case 5.

TABLE C1

INITIAL CONDITIONS FOR THE BASE CASE OF THE
RELAP5 CALCULATIONS OF THE HFBR

<u>Variable</u>	<u>Design Basis Value</u>	<u>Anticipated Variation</u>	<u>Uncertainty</u>	<u>RELAP5 Base Case</u>
Reactor Power (MW)	61	59-61	$\pm 5\%$	64.05
Primary Flow Rate (gpm)	17,900	17900-18500	$\pm 3\%$	17,400
Cover Gas Pressure (psig)	200	200-210	± 5	195
Liquid Level (inches)	230	230-240	± 1	241
Core Inlet Temperature ($^{\circ}\text{C}$)	56.5 (133.8 $^{\circ}\text{F}$)	50-56.5	± 1	57.5 (135.5 $^{\circ}\text{F}$)

Figure C1 RELAP5 Node Diagram of the HFBR Vessel and Primary Loop

Figure C2.1

Primary Pump Angular Velocity
(Base Case 64.05 MW)

Figure C2.2

Primary Flow
(Base Case 64.05 MW)

Figure C2.3

Mass Flow Rate at Top of Heated Channel
(Base Case 64.05MW)

Figure C2.4

Mass Flow Rate at Bottom of Heated Channel
(Base Case 64.05MW)

Figure C2.5

Mass Flow Rate at Top of Heated Channel
(Base Case 64.05MW)

Figure C2.6

Mass Flow Rate at Top of Heated Channel
(Base Case 64.05MW)

Figure C2.7

Mass Flow Rate at Bottom of Heated Channel (Base Case 64.05MW)

Figure C2.8

Mass Flow Rate at Bottom of Heated Channel
(Base Case 64.05MW)

Figure C2.9

Mass Flow Rate through Flow Reversal Valve
(Base Case 64.05MW)

Figure C2.10

Mass Flow Rate of Core Bypass Flow
(Base Case 64.05MW)

Figure C2.11

Normalized Flow Area of Flow Reversal Valve
(Base Case 64.05MW)

Figure C2.12

Normalized Flow Area of Primary Check Valve
(Base Case 64.05MW)

Figure C2.13

Instantaneous Channel Void Fraction
(Base Case 64.04 MW)

Figure C2.14

Instantaneous Channel Void Fraction
(Base Case 64.04 MW)

Figure C2.15

Instantaneous Channel Void Fraction
(Base Case 64.04 MW)

Figure C2.16

Local Void Fraction in Heated Section of Hot Channel Group #1
(Base Case 64.05 MW)

Figure C2.17

Local Void Fraction in Heated Section of Hot Channel Group #1
(Base Case 64.05 MW)

Figure C2.18

Local Void Fraction in Heated Section of Hot Channel Group #1
(Base Case 64.05 MW)

Figure C2.19

Local Void Fraction in Heated Section of Hot Channel Group #1
(Base Case 64.05 MW)

Figure C2.20

Fri Apr 7 16:54:54 1995

Time Averaged Void Fraction

Figure C3.1

Fri Apr 7 16:55:32 1995

Time Averaged Void Fraction

Figure C3.2

Fri Apr 7 16:56:05 1995

Time Averaged Void Fraction

Figure C3.3

Fri Apr 7 16:57:26 1995

Time Averaged Void Fraction

Figure C3.4

Fri Apr 7 16:57:59 1995

Time Averaged Void Fraction

Figure C3.5

Fri Apr 7 16:58:38 1995

Time Averaged Void Fraction

Figure C3.6

Fri Apr 7 16:59:14 1995

Figure C3.7

Fri Apr 7 16:59:50 1995

Time Averaged Void Fraction

Figure C3.8

Fri Apr 7 17:00:23 1995

Time Averaged Void Fraction

Figure C3.9

Figure C3.10

Figure C4

Mon Apr 3 15:09:46 1995

Time Averaged Channel Void Fraction

Figure C5.1

Mon Apr 3 15:12:21 1995

Time Averaged Channel Void Fraction

Figure C5.2

Mon Apr 3 15:13:54 1995

Time Averaged Channel Void Fraction

Figure C5.3

Mon Apr 3 15:20:07 1995

Time Averaged Channel Void Fraction

Figure C5.4

Mon Apr 3 15:24:23 1995

Time Averaged Channel Void Fraction

Figure C5.5

Mon Apr 3 15:25:31 1995

Time Averaged Channel Void Fraction

Figure C5.6

Mon Apr 3 15:14:45 1995

Time Averaged Channel Void Fraction

Figure C5.7

Mon Apr 3 15:27:12 1995

Time Averaged Channel Void Fraction

Figure C5.8

Figure C5.9

Mon Apr 3 15:16:19 1995

Time Averaged Channel Void Fraction

Figure C5.10

Figure C6.1

Tue Apr 4 08:25:41 1995

Time Averaged Void Fraction

Figure C6.2

Time Averaged Void Fraction

Figure C6.3

Tue Apr 4 08:28:35 1995

Time Averaged Void Fraction

Figure C6.4

Tue Apr 4 08:29:23 1995

Time Averaged Void Fraction

Figure C6.5

Tue Apr 4 08:31:28 1995

Time Averaged Void Fraction

Figure C6.6

Figure C6.7

Tue Apr 4 08:32:58 1995

Time Averaged Void Fraction

Figure C6.8

Tue Apr 4 08:33:45 1995

Time Averaged Void Fraction

Figure C6.9

Fri Apr 7 16:49:35 1995

Time Averaged Void Fraction

Figure C6.10

Mon Apr 10 16:35:00 1995

Time Averaged Void Fraction

Time, sec.

Figure C7.1

Mon Apr 10 16:35:48 1995

Figure C7.2

Mon Apr 10 16:36:18 1995

Time Averaged Void Fraction

Figure C7.3

Mon Apr 10 16:36:45 1995

Time Averaged Void Fraction

Figure C7.4

Mon Apr 10 16:37:15 1995

Time Averaged Void Fraction

Figure C7.5

Mon Apr 10 16:37:41 1995

Figure C7.6

Mon Apr 10 16:38:12 1995

Time Averaged Void Fraction

Figure C7.7

Mon Apr 10 16:38:40 1995

Time Averaged Void Fraction

Figure C7.8

Mon Apr 10 16:39:10 1995

Time Averaged Void Fraction

Time, sec.

Figure C7.9

Mon Apr 10 16:39:41 1995

Time Averaged Void Fraction

Figure C7.10

Figure C8.1

Tue Mar 21 16:04:26 1995

Time Averaged Void Fraction

Figure C8.2

Tue Mar 21 16:06:14 1995

Time Averaged Void Fraction

Figure C8.3

Tue Mar 21 16:07:28 1995

Time Averaged Void Fraction

Figure C8.4

Tue Mar 21 16:16:38 1995

Time Averaged Void Fraction

Time, sec.

Figure C9.1

Tue Mar 21 16:17:24 1995

Time Averaged Void Fraction

Figure C9.2

Figure C9.3

Figure C9.4

Time Averaged Void Fraction

Figure C10.1

Tue Mar 21 16:26:09 1995

Time Averaged Void Fraction

Figure C10.2

Tue Mar 21 16:26:47 1995

Time Averaged Void Fraction

Figure C10.3

Tue Mar 21 16:27:26 1995

Time Averaged Void Fraction

Figure C10.4