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ANALYSIS OF FLOW REVERSAL TEST

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ABSTRACT

A series of tests has been conducted to measure the dryout power associated with a flow transient whereby the coolant in a heated channel undergoes a change in flow direction. An analysis of the test was made with the aid of a system code, RELAP5. A dryout criterion was developed in terms of a time-averaged void fraction calculated by RELAP5 for the heated channel. The dryout criterion was also compared with several CHF correlations developed for the channel geometry.

INTRODUCTION

In support of the High Flux Beam Reactor (HFBR) tests have been performed in a heated vertical rectangular channel to study the flow reversal process. In a flow reversal, the coolant undergoes a flow transition from forced convection downflow to natural circulation upflow. The thermal limit (dryout power) was measured in these tests during the flow reversal process. The purpose of the test program was to revise and update the technical basis for the operating power of the HFBR.

The thermal hydraulic system code RELAP5 mod 3 was used to perform numerical simulation of these tests. A modification of RELAP5, involving a reduction in the interfacial heat transfer coefficient, was required to limit the code from calculating severe pressure transients which were not supported by the test data.

An empirical criterion was developed to correlate dryout power with time-averaged channel void fraction calculated by RELAP5. The criterion has also been checked against steady-state critical heat flux (CHF) correlations developed elsewhere for conditions similar to the tests and the HFBR.

THE FLOW REVERSAL TEST

The flow reversal tests were conducted at the Heat Transfer Research Facility (HTRF) of Columbia University. These tests were designed to simulate the flow reversal transient in the HFBR. The HFBR is a research reactor at Brookhaven National Laboratory (BNL). It has been in operation since 1965 and is being used by scientists for neutron scattering, nuclear physics and irradiation studies. The core of the reactor is composed of 28 plate-type fuel elements. The coolant channels are rectangular in shape and they are about 0.1 inch thick, 2.5 inch wide, and 24 inches high. The normal coolant flow, as indicated in Figure 1, is downward through the core. Upon loss of forced flow, four spring-loaded valves inside the reactor vessel will open automatically thereby providing a closed fluid circuit for natural circulation. A flow reversal occurs when the downward core flow reaches a value at which the thermal buoyancy head is comparable to the friction losses in the core.

In passing through the low flow period of a flow reversal transient there is a degradation in the heat removal capability of the coolant in the core channels. The test program was designed to capture, as closely as possible, the essential features of the flow reversal transient in the reactor, and to determine the thermal limit for flow reversal under a number of different test conditions. Details of the test loop and the test procedure have been reported elsewhere [1] and only a brief description of the test will be given here.

The test loop was a full-height representation of the natural circulation flow path in the HFBR vessel. Figure 2 is a schematic of the test loop for one of the test series. The tests were performed with an electrically heated single channel section representing the core, an orifice (or valve) 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 top of the upper plenum region was open to the atmosphere. Demineralized water was the working fluid of the test.

Instrumentation was installed to monitor the temperature, pressure and flow rate of the coolant. Each heater plate (representing the fuel plate) was monitored for current, voltage, and wall temperatures by nine thermocouples evenly spaced along the vertical centerline of the plate. 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.

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.

In the second and third series of tests the test loop was modified to expand the range of the bypass ratio. 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 the third test series. 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 via a secondary bypass line (see Figure 2) so that it mixed with the hot water exiting the test section.

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.

A summary of the test results is presented in Table 1. Each set of test conditions is associated with a pair of results. 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.

Depending on the test conditions the threshold power (highest power for successful flow reversal) varies from 7 to 19 kW. 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/or 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 (test condition 17) with low impedance in the bypass path. For the pump trip tests the coastdown time is short ($\approx$ 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 dryout power for the two-sided heating test is only a few percent higher than that for the single-sided heating test. This indicates that the thermodynamic condition of the fluid as determined by the power input is much more important than local heat flux in determining dryout.

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 3. The four stages of a flow reversal transient are:

1. <u>Coastdown Stage</u>

   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. <u>Vapor Generation Stage</u>

   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 few cases that were conducted at higher powers, a power trip occurred before the flow reversal.

RELAP5 ANALYSIS OF THE TEST

As part of the program to quantify the flow reversal thermal limit, an effort was started to develop a model to predict dryout during flow reversal. Simulations of the flow reversal tests were performed by using the system thermal-hydraulics code RELAP5 [2]. As a result of the numerical analysis of the test, an empirical dryout parameter, based on the calculated void fraction in a channel during flow reversal, has been developed.

A RELAP5 representation of the test loop is shown in Figure 4. Initial results from the simulation of flow reversal by RELAP5 mod 3.1 and mod 3.1.1 were unsatisfactory. When the calculation proceeded past the initial transition from downflow to upflow (flow reversal), pressure spikes began to appear periodically in the hydrodynamic volumes. This was accompanied by fairly high mass flow rates of water into and out of the heated section. As a result, the coolant in the heated section alternated between periods of mostly steam and periods of liquid only. However, no pressure spikes or high mass flow rate was observed or recorded during the actual tests [1]. This led to the search for an area of deficiency in the models and correlations in RELAP5. The high mass flow rates and pressure spikes were found to be a consequence of rapid pressure reduction due to high rates of steam condensation at the interface between steam and subcooled water.

Numerical experimentation with RELAP5 mod 3.1.1 showed that by reducing the interfacial heat transfer coefficients in the flow regimes of subcooled bubbly flow and subcooled slug flow the pressure spikes and high water flow rates were eliminated in the simulation of the flow reversal tests. An examination of the correlations for the interfacial heat transfer coefficients in RELAP5 suggests that there are bases for reducing the coefficients.

For the subcooled liquid in the bubbly flow regime RELAP5 (mod 3.1.1 and 3.1.1.1) uses a modified form of Unal's correlation for the interfacial heat transfer coefficient and it is expressed in the form [3,4],

$$H_{if} = \frac{\alpha\ F_s\ h_{fg}\ \rho_f\ \rho_g}{\rho_f - \rho_g} \qquad (1)$$

In RELAP5 the empirical coefficient F_s is formulated as a function of system pressure, liquid phase velocity, and void fraction. Its value decreases exponentially from the maximum at $\alpha = 0.0$ to a constant value of 0.075 for $\alpha \geq 0.25$. As a means of reducing the heat transfer coefficient, a modification has been made in subroutine 'hifbub' of RELAP5 to replace the empirical coefficient F_s with a constant value of 0.075.

In RELAP5 the volumetric interfacial heat transfer coefficient for the slug subcooled liquid is a combination of two terms, one from the bubbly subcooled liquid and the other from the Taylor bubble [3].

$$H_{if} = H_{if,bub} + H_{if,TB} \qquad (2)$$

The contribution from the bubbly liquid, $H_{if,bub}$, is the same as for the bubbly subcooled liquid described above. The contribution from the Taylor bubble, $H_{if,TB}$, is a function of the Reynolds and Prandtl numbers. RELAP5 adopts a dimensionless constant of 1.18942 which lies between the laminar Seider-Tate correlation coefficient, 1.86, and the turbulent Dittus-Boelter coefficient, 0.023. If the liquid flow past a Taylor bubble is in the turbulent regime, the constant in RELAP5 is reduced by a factor of about 50 (1.18942/0.023 = 51.7). It appears a factor of 50 reduction in the Taylor bubble contribution to the interfacial heat transfer coefficient is consistent with the original formulation in RELAP5. A modification has been made in subroutine 'phantv' of RELAP5 to reduce, by a factor of 50, the interfacial heat transfer coefficient for the Taylor bubble part in the slug subcooled liquid flow regime.

Comparisons between RELAP5 calculations before and after the modifications are shown in a series of figures. The figures are generated for a flow reversal test at 7 kW with single-sided heating. For this set of test conditions, (test condition 1) the flow reversal was successful without a power trip for more than two

TABLE 1

SUMMARY OF FLOW REVERSAL TEST RESULTS

TEST* CONDITION	TEST# OUTCOME	CHANNEL POWER (kW)	BYPASS## RATIO	TOTAL INITIAL FLOW (gpm)	INLET TEMP. (F)	COASTDOWN TIME (sec.)	MAXIMUM++ VOID FRACTION
1 (1)	FR	7.0	2:1	3	130	40	0.696
1 (1)	Trip	7.6	2:1	3	130	40	0.761
2 (1)	FR	7.6	2:1	3	130	30	0.716
2 (1)	Trip	8.4	2:1	3	130	30	0.789
3 (1)	FR	8.3	2:1	3	110	40	0.704
3 (1)	Trip	9.1	2:1	3	110	40	0.771
4 (1)	FR	6.9	2:1	3	130	40	0.762
4 (1)	Trip	7.8	2:1	3	130	40	0.829
5 (1)	Trip	6.8	5:1	3	130	40	0.884
5 (1)	FR	6.4	5:1	3	130	40	0.860
6 (1)	FR	7.9	1.5:1	3	130	40	0.739
6 (1)	Trip	8.2	1.5:1	3	130	40	0.766
7 (2)	FR	7.5	1.42:1	3.4	130	40	0.819
7 (2)	Trip	8.5	1.42:1	3.4	130	40	0.904
8 (2)	Trip	7.4	1.42:1	3.4	130	60	0.851
8 (2)	FR	6.7	1.42:1	3.4	130	60	0.777
9 (2)	Trip	6.9	2.78:1	3.4	130	40	0.895
9 (2)	FR	6.7	2.78:1	3.4	130	40	0.894
10 (1)	FR	8.3+	2:1	3	130	40	0.784
10 (1)	Trip	8.9+	2:1	3	130	40	0.819
11 (1)	Trip	7.3+	2:1	3	150	40	0.824
11 (1)	FR	6.4+	2:1	3	150	40	0.743
12 (1)	Trip	7.5+	2:1	3	130	60	0.775
12 (1)	FR	6.9+	2:1	3	130	60	0.701
13 (3)	FR	9.0	2:1:0	3	130	40	0.713
13 (3)	Trip	9.8	2:1:0	3	130	40	0.774
14 (3)	FR	13.8	1:3.4:0	8.8	130	40	0.860
15 (3)	FR	13.8	1:3.4:0.6	10	130	40	0.668
16 (3)	FR	11.5	2:1:1.2	4.2	125	40	0.55
16 (3)	Trip	13.2	2:1:1.2	4.2	130	40	0.667
17 (3)	FR	19.0	1:3.4:0.6	10	130	1.5	0.718

Notes:

* The number in parenthesis after the test condition number indicates the sequence in the test series.
\# FR means a successful flow reversal without a power trip for 30 seconds after initiation of flow reversal.
\+ Two-sided heating test.
\## Refers to ratio of flow rates under initial conditions. First number applies to heated section flow, second number applies to primary bypass flow and the third, if present, applies to secondary bypass flow.
\++ Maximum time-averaged void fraction during the 10 second interval following reversal in RELAP5 calculation. The time averaging period is two seconds.

minutes after the initiation of flow coastdown. It was observed during the test that natural circulation was achieved shortly after the initiation of flow reversal. There were noticeable fluctuations in the natural circulation flow through the heated section of the test loop. The boiling boundary was seen to move continuously up and down the heated section. However, the top portion of the heated section was always in two-phase and only the bottom portion was in single-phase.

The following observations illustrate the major improvements in the RELAP5 calculation as a result of the changes in the heat transfer coefficients.

1. After the modifications, no large swings in the wall temperature are calculated (see Figure 5). The calculation shows that the heater wall stays essentially just above the saturation temperature as recorded in the test.

2. Mass flow through the heated section reflects a quasi-steady natural circulation upflow after flow reversal (see Figure 6).

3. The channel void fraction in Figure 7 shows that by using the modified heat transfer coefficient the heated section is never totally occupied by single-phase liquid after the flow reversal. The fluctuations in void fraction correspond to the movement of the boiling boundary observed during the test.

4. Pressure fluctuations are limited and they do not drop below the atmospheric pressure (see Figure 8).

A list of flow reversal tests that have been simulated by the modified version of RELAP5 (based on mod 3.1.1.1) is shown in Table 1. The numerical simulations 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.

The four stages of a flow reversal transient is demonstrated in Figure 9 which shows the mass flow rate at the top and bottom of the heated section. The corresponding figures for wall temperature and channel void fraction have been shown earlier in Figures 5 and 7 respectively. These figures are for a case of flow reversal in a 7 kW channel with a coastdown period of 40 seconds. In Figure 9 quasi-steady state natural circulation flow appears to have been established shortly after the forced flow ended at 45 seconds. Flow and channel void fraction oscillations have been observed both experimentally and in the RELAP5 calculations. The observed oscillation period of approximately 2 seconds can be shown to be roughly equal to the time it takes to heat up the coolant in a channel to saturation.

An excursion in wall temperature is a good indicator of a potential dryout condition. However, in the simulation of flow reversal RELAP5 tends to over-predict the transient temperature response of the heated wall. 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 lieu of wall temperature an alternate dryout criterion has been developed using the channel void fraction as an indicator.

CHANNEL VOID FRACTION AS DRYOUT CRITERION

The use of channel void fraction as a criterion for dryout was suggested by Griffith, et.al. [5] in a correlation 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. 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 for the flow reversal transient. These considerations led to the following formulation of the dryout criterion based on channel void fraction during flow reversal.

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. The instantaneous channel void fraction is defined as an arithmetic mean of the void fraction in the heated section. 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 10, which is based on a simulation of one of the test runs (test condition 1). 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 1. The maximum time averaged void fraction for each of the test simulations is shown in this table and also plotted in Figure 11. 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 $\overline{x} = 0.75$ and $s = 0.083$. The no dryout threshold values range from 0.55 to 0.89. A 95/95% lower tolerance one-sided 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 test condition 14, 15, and 17 in Table 1, a power trip occurred 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, test condition 17, 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 three cases of power trip.

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 for comparison. Three CHF correlations were selected for comparison with the void-based dryout criterion. They are the correlations developed by Mishima and Nishihara [7], Sudo, et.al. [8], and Oh and Englert [9]. 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. The results are shown in Figure 12. The differences in void fractions calculated for a given mass flux reflect the different dryout power predicted by the correlations. However the channel void fractions 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 flow reversal tests.

CONCLUSIONS

A series of experiments has established the dryout power for flow reversal in a narrow vertical rectangular channel under a variety of test conditions. In conjunction with these tests a RELAP5 model of the test loop was developed.

As a result of the experimental and the RELAP5 analyses an empirical dryout parameter based on the calculated void fraction has been developed. 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 tests. The void fraction criterion has also been tested against steady state CHF correlations developed elsewhere for conditions similar to the HFBR. The steady state void fractions calculated fell within the range of the 2 second void fractions determined from the RELAP5 simulations of the tests.

The dryout criterion developed here can be applied in conjunction with a RELAP5 analysis to establish the maximum power level for HFBR such that adequate core cooling can be assured for flow reversal transients.

ACKNOWLEDGEMENTS

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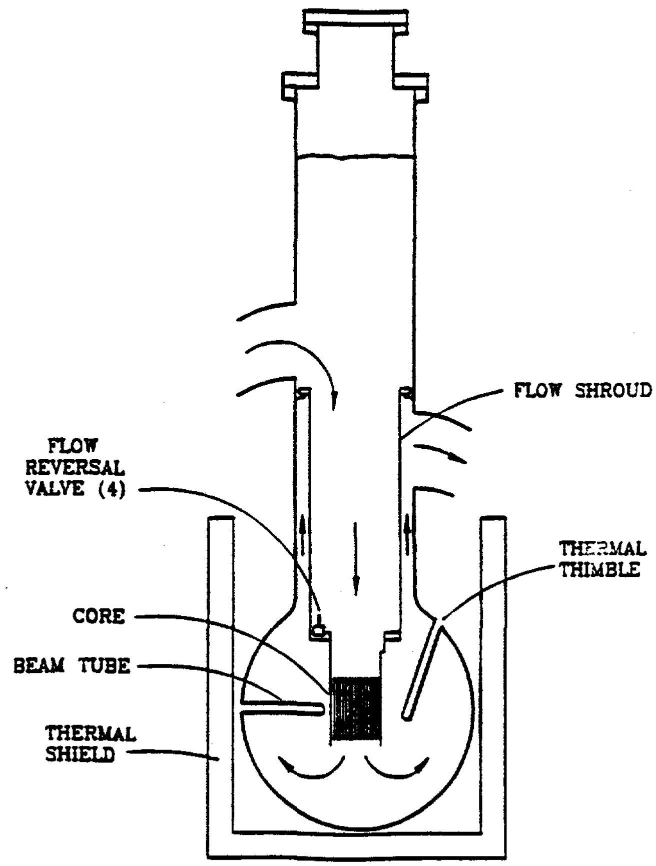

Figure 1: HFBR Vessel Showing Normal Flow Direction

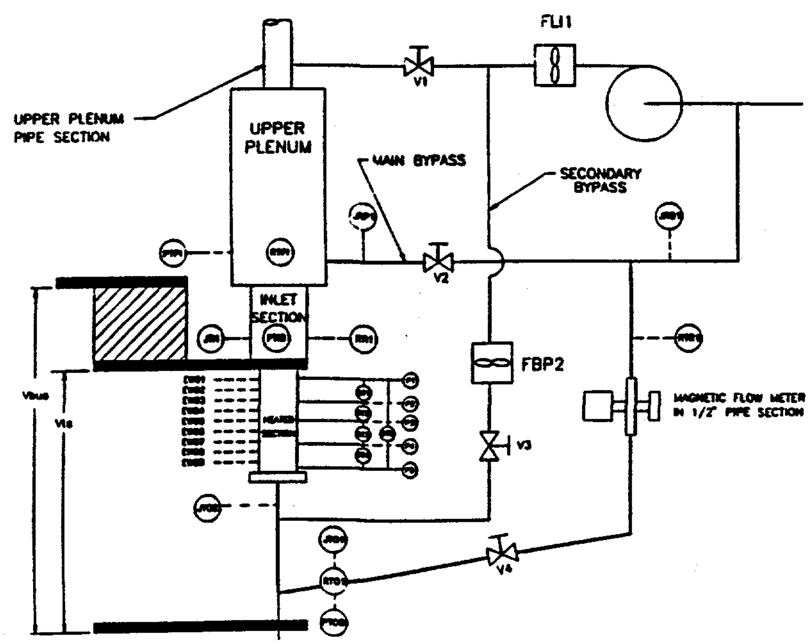

Figure 2: Schematic of Test Loop for Extended Bypass Ratio Tests

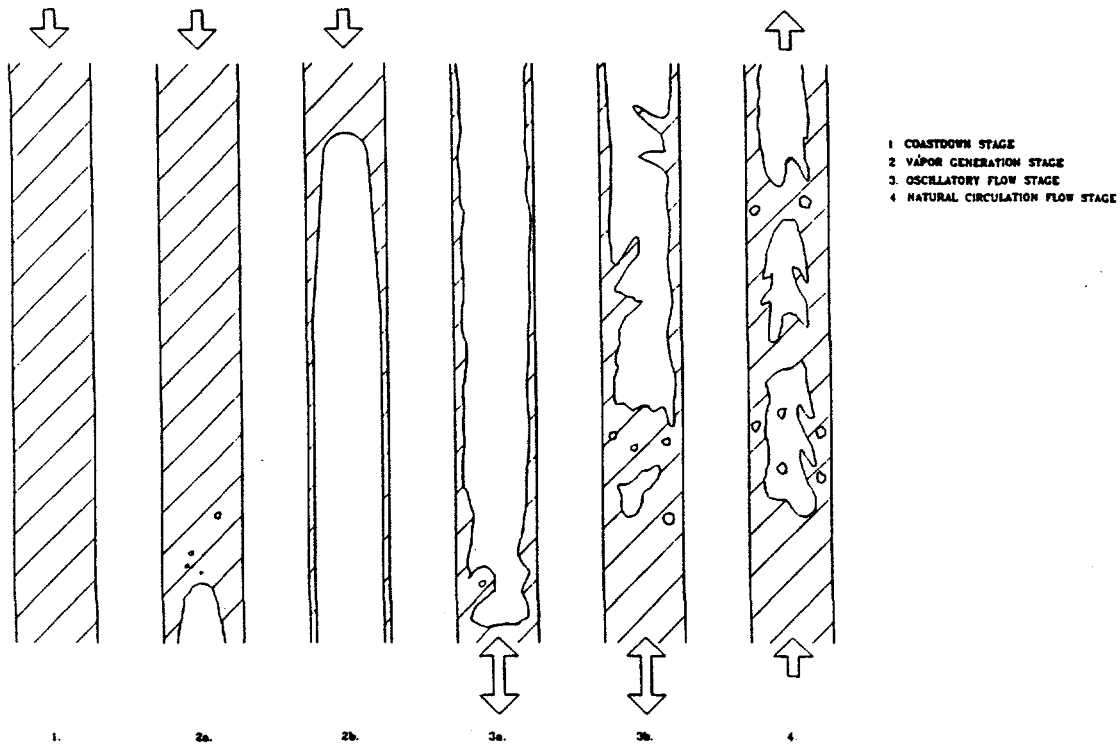

Figure 3: Stages of the Flow Reversal Process

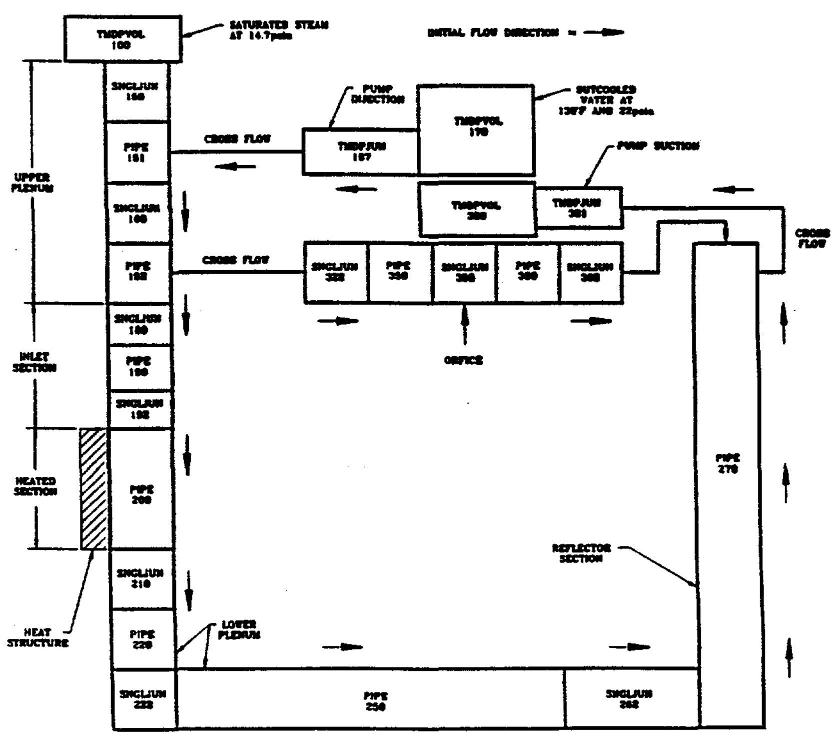

Figure 4: RELAP5 Representation of the Flow Reversal Test

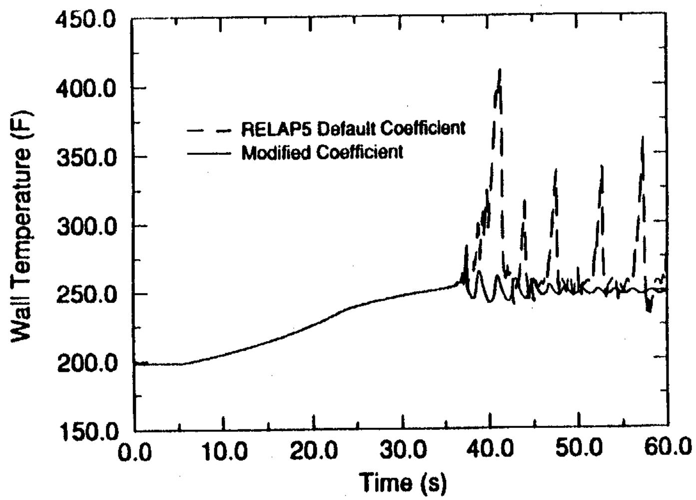

Figure 5: Heater Wall Temperature (at Mid-Height) Calculated by RELAP5

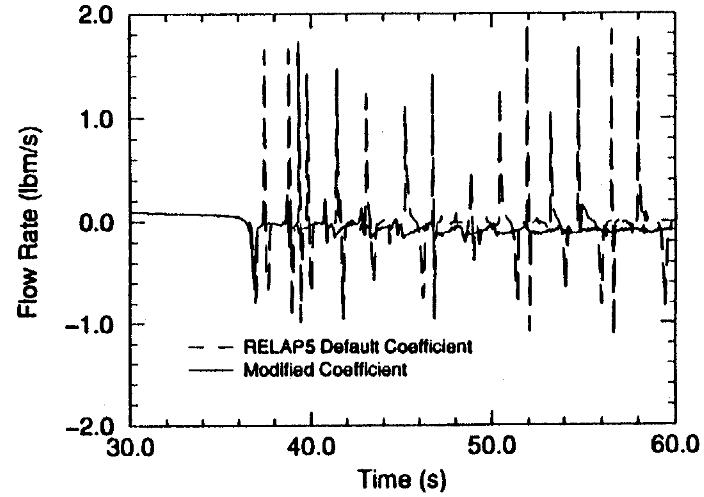

Figure 6: Mass Flow Rate Calculated by RELAP5 at Top of Heated Channel

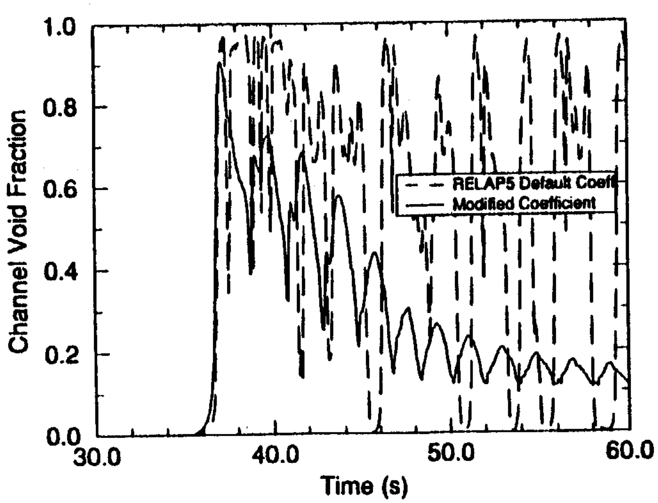

Figure 7: Void Fraction Calculated by RELAP5 in Heated Channel

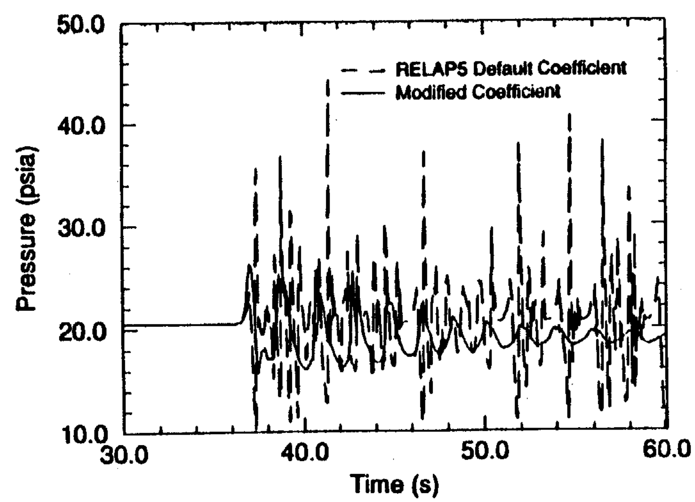

Figure 8: Pressure Calculated by RELAP5 at Bottom of Upper Plenum

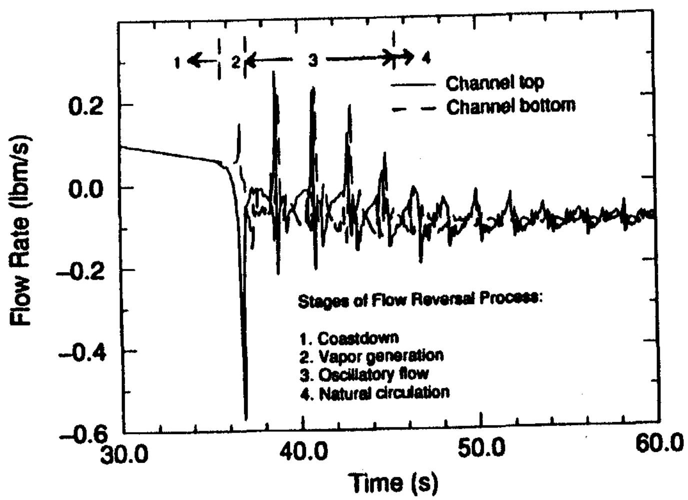

Figure 9: Mass Flow Rate Calculated by RELAP5 at Top and Bottom of Heated Channel

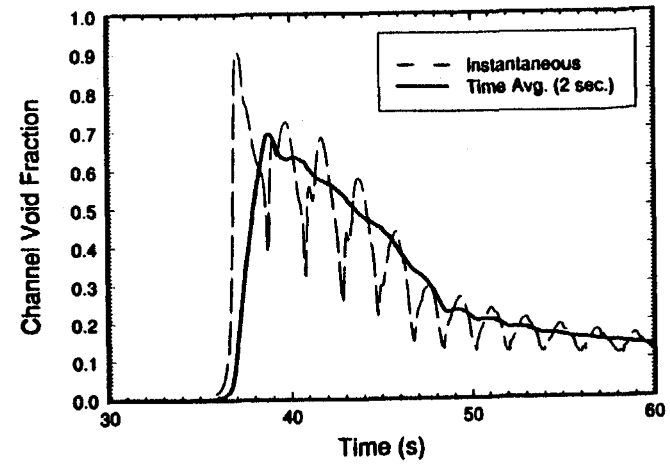

Figure 10: Typical Trace of Time Averaged Channel Void Fraction

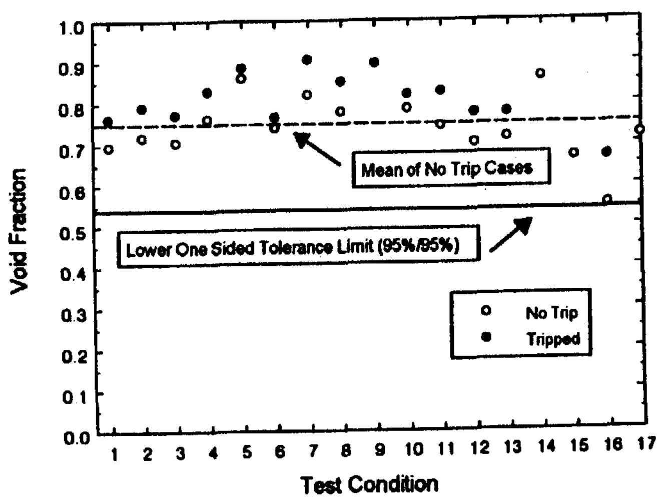

Figure 11: Maximum Time Averaged Channel Void Fraction for Different Test Conditions

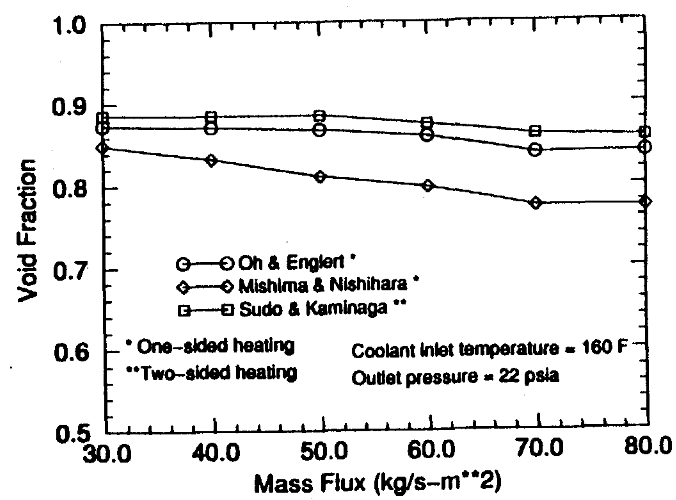

Figure 12: Channel Void Fraction Corresponding to Dryout Power Predicted by Various Correlations