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ANL/RERTR/TM-11-23

Comparison of the PLTEMP Code Flow Instability Predictions with Measurements Made with Electrically Heated Channels for the Advanced Test Reactor

Nuclear Engineering Division

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by
E.E. Feldman
Nuclear Engineering Division, Argonne National Laboratory

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Summary

Croft[1] and Waters[2] used tests in electrically heated channels to measure the onset of fuel burnout, caused by flow instability, in the Advance Test Reactor. An earlier version (version 3.0) of the PLTEMP/ANL code**Error! Reference source not found.** is used to predict the onset of flow instability in 42 of these tests. The ability of the code to predict flow instability in these tests reasonably accurately, as well as the ability of the code to predict the onset of flow instability as measured in other electrically heated tests[3,6,7], as reported by Olson,[5] lead to the conclusion that the code should be able to predict the onset of flow instability reasonably well for the University of Missouri Research Reactor (MURR) after it is converted from HEU to LEU fuel.

1. Introduction

When the University of Missouri Research Reactor (MURR) was designed in the 1960s the potential for fuel element[a] burnout by a phenomenon referred to at that time as "autocatalytic vapor binding" was of serious concern. This type of burnout was observed to occur at power levels considerably lower than those that were known to cause critical heat flux. The conversion of the MURR from HEU fuel to LEU fuel will probably require significant design changes, such as changes in coolant channel thicknesses, that could affect the thermal-hydraulic behavior of the reactor core. Therefore, the redesign of the MURR to accommodate an LEU core must address the same issues of fuel element burnout that were of concern in the 1960s.

The Advanced Test Reactor (ATR) was designed at about the same time as the MURR and had similar concerns with regard to fuel element burnout. These concerns were addressed in the ATR by two groups of thermal-hydraulic tests that employed electrically heated simulated fuel channels[1,2]. The Croft (1964), Reference 1, tests were performed at ANL. The Waters (1966), Reference 2, tests were performed at Hanford Laboratories in Richland Washington. Since fuel element surface temperatures rise rapidly as burnout conditions are approached, channel surface temperatures were carefully monitored in these experiments. For self-protection, the experimental facilities were designed to cut off the electric power when rapidly increasing surface temperatures were detected. In both the ATR reactor and in the tests with electrically heated channels, the heated length of the fuel plate was 48 inches, which is about twice that of the MURR.

Whittle and Forgan (1967)[3] independently conducted tests with electrically heated rectangular channels that were similar to the tests by Croft and by Walters. In the Whittle and Forgan tests the heated length of the channel varied among the tests and was between 16 and 24 inches. Both Waters and Whittle and Forgan show that the cause of the fuel element burnout is due to a form of flow instability. Whittle and Forgan provide a formula that predicts when this flow instability

[a] For research reactors it is common to refer to "fuel assemblies" as "fuel elements". This can be confusing because in other applications a fuel element is only a single fuel rod or plate.

will occur. This formula is included in the PLTEMP/ANL code.**Error! Reference source not found.** Olson[5] has shown that the PLTEMP/ANL code accurately predicts the powers at which flow instability occurs in the Whittle and Forgan experiments. He also considered the electrically heated tests performed in the ANS Thermal-Hydraulic Test Loop at ORNL and report by M. Siman-Tov et al.[6,7]

The purpose of this memorandum is to demonstrate that the PLTEMP/ANL code accurately predicts the Croft and the Waters tests. This demonstration should provide sufficient confidence that the PLTEMP/ANL code can adequately predict the onset of flow instability for the converted MURR. The MURR core uses light water as a coolant, has a 24-inch active fuel length, downward flow in the core, and an average core velocity of about 7 m/s. The inlet temperature is about 50° C and the peak outlet is about 20° C higher than the inlet for reactor operation at 10 MW. The core pressures range from about 4 to about 5 bar. The peak heat flux is about 110 W/cm^2.

Section 2 describes the mechanism that causes flow instability. Section 3 describes the Whittle and Forgan formula for flow instability. Section 4 briefly describes both the Croft and the Waters experiments. Section 5 describes the PLTEMP/ANL models. Section 6 compares the PLTEMP/ANL predictions based on the Whittle and Forgan formula with the Croft measurements. Section 7 does the same for the Waters measurements. Section 8 provides the range of parameters for the Whittle and Forgan tests. Section 9 discusses the results and provides conclusions.

2. Mechanism for Flow Instability

Figure 1, which is patterned after Reference 3, shows the mechanism for flow instability. The flow demand curve, which is the thick black curve that is labeled "Zero Power System Resistance Curve," exhibits the classic isothermal situation where liquid water flows through an unheated channel and the pressure drop increases monotonically with the flow rate.

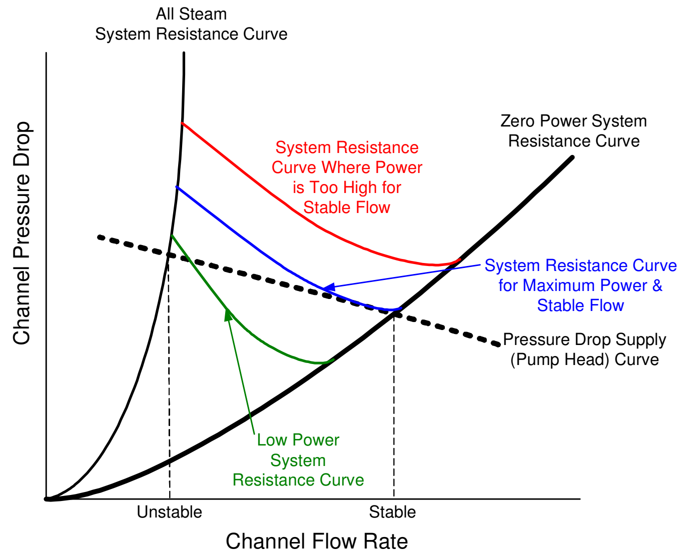

Figure 1. Illustration of Excursion-Flow (Ledinegg) Instability

The black dashed "Pressure Drop Supply (Pump Head) Curve" curve represents the pressure differential at each flow rate that is available to drive the flow through the channel. For the zero power case the operating point must be at the intersection of these two curves and is noted by the word "Stable" on the abscissa. If the channel is heated, then at some sufficiently low flow rate subcooled nucleate boiling will begin to occur in the channel and vapor formation will be increase as the flow is reduced further. This boiling causes the hydraulic resistance and the pressure drop in the channel to increase with decreasing flow. Thus, the lower part of the "Zero Power System Resistance Curve," is replaced by the red (upper), blue (middle), or green (lower) extensions, depending on the channel power level. The green extension represents a stable flow condition because boiling begins when the flow rate is considerably below the labeled "Stable" operating flow. The blue curve is the highest stable power. For power levels above this power, the red extension, for example, the resistance and the pressure drop supply curves do not intersect. In this instance much of the channel length can be in an all-steam condition. The "All-Steam System Resistance Curve" curve, where the pressure drop is much greater for a given flow than it is for the zero-power curve, is representative of this condition. For this condition the channel flow tends to be determined by the intersection of the all-steam curve and the dashed pressure drop supply curve. The intersection is indicated by the word "Unstable" on the abscissa. Thus, when the power is increased to slightly above that represented by the blue curve, there can be rapid reduction in channel flow rate, which can lead to a channel burn-out condition.

In a system with multiple parallel channels, such as a research reactor, the reduction in flow in one channel may not appreciably affect the total reactor flow rate. However, the large reduction in flow and the resultant excessive temperatures in one unstable channel can cause higher temperatures and flow instability in its immediate neighbors. Thus, a flow instability in one channel can propagate to other channels.

3. Whittle and Forgan formula for predicting flow instability

Based on Whittle and Forgan,[3] flow instability is predicted to occur when ΔTc / ΔTsat = R, where ΔTc is the bulk water temperature rise from the channel inlet to the exit, ΔTsat is the difference between coolant inlet temperature and the local coolant saturation temperature at the exit, and R is given by:

$$R = \frac{1}{1 + \eta / \left(L_H / D_H \right)} \qquad (1)$$

where η is a positive constant, L_H is the heated length of the channel, and D_H is the heated diameter. The heated length is the length of the fuel meat. The heated diameter is four times the channel flow area divided by the heated perimeter, which is the perimeter of fuel meat in the channel cross section (i.e., twice the width of the fuel meat when there are two fuel plates of equal width).

A key issue is the selection of the constant η, which determines the value of R. As η is increased R goes toward zero and the allowed exit bulk coolant temperature approaches the inlet temperature. As η is decreased toward zero, R goes toward 1 and the allowed exit bulk coolant temperature approaches the saturation temperature. Reference 5 performed a statistical analysis of the 74 applicable experiments in Reference 3 and found that there is a 95% confidence interval that 95% of the rectangular channel data measured by future Reference 3 type of measurements will not exceed an η value of 31.09. Reference 5 recommends that for consistency with INTERATOM[8] that a value of 32.5 be used for η, even though it is more conservative than the 31.09 value. Therefore, the recommended 32.5 value was used in the current analysis.

In the Whittle and Forgan experiments with rectangular channel of R was found to be between 0.78 and 0.88. This implies that flow instability is expected to occur when the coolant temperature rise from the channel inlet to the exit is between 78 and 88% of the temperature difference between the coolant inlet temperature and the coolant saturation temperature.

In the PLTEMP/ANL code the flow instability ratio (FIR) is provided in the output and is defined to be the ratio of R to (ΔTc / ΔTsat), where R is obtained from equation 1. Typically, multiple runs of the code would be made at various steady-state power levels until an FIR of 1 is obtained. The margin to flow instability is then taken to be the ratio of the channel power that produced an FIR of 1 to the channel power when the reactor is operating at its nominal full power.

4. Croft and Waters experiments

In the ATR the fuel elements are longitudinally straight with fuel plates that are laterally curved so the element forms a 45° wedge of a concentric annulus. Croft simulated a curved fuel channel of the ATR with a single flat duct that was electrically heated from the two opposing longer sides. The duct was 1.20 inches wide with electrical heating along the middle 1.00 inches, but not along the thickness. The electric heaters produced a uniform heat flux along the width of the heated 1.00 inches. The axial heat flux shape was a chopped cosine with a peak to average of 1.4 so that the peak heat flux occurred at the middle of the 48-inch heated length and the heat flux was symmetric about the middle. Separate experiments were made with duct thicknesses of 0.054, 0.072, and 0.094 inches. The Waters tests used the same axial heat flux shape and heated length as the Croft tests. The Waters duct was 2.10 inches wide and was heated along the middle 2.00 inches of the two longer sides, but not along the thickness. The Waters tests included only a 0.070-inch thick duct size. The Waters tests used two test sections, one in which the electrical heat generation rate along the heated surface did not vary along the width of the duct and a second one in which it did vary. In both test sections one of the two heated plates was deliberately designed to produce several percent more power than the other.

Waters provides a graph which shows the lateral distribution of heat flux of each the two heated plates of the second test section. For purposes of analysis, we divided the heated width of each plate in the second test section into ten strips of equal width. From the graph for each plate we estimated the relative heat flux per strip, where the average heat flux for the entire width corresponds to 1.0, and found that the both plates have nearly the same relative heat flux distribution. Figure 2, shows that average of the two relative lateral heat flux distributions.

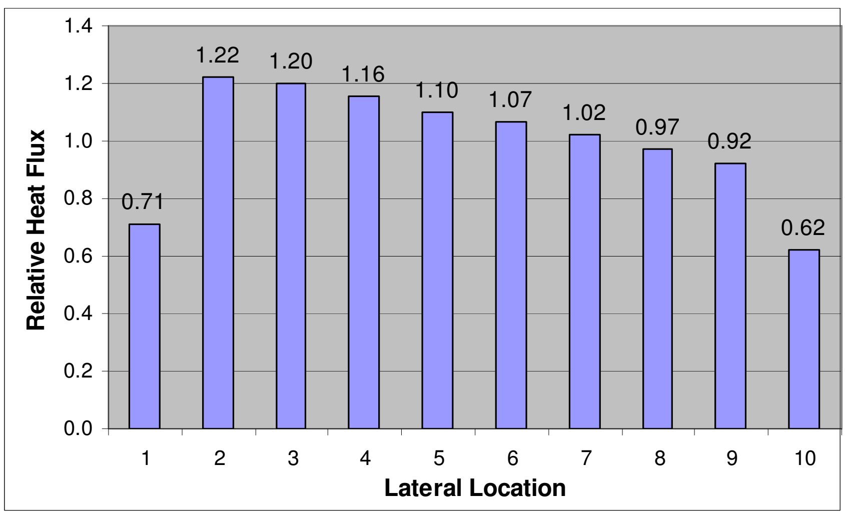

Figure 2. Lateral Heat Flux Distribution in Non Uniform Waters Test Section

From both the Croft and the Waters reports one is provided or can deduce for each experiment the measured inlet and outlet pressures and temperatures, the power, and the flow rate where flow instability was measured to occur. In all of the tests the water flowed from the top of the section to the bottom. Waters was aware of the Figure 1 flow instability phenomenon and provided plots of system resistance curves. Croft, on the other hand, seemed to merely search for the point where a sudden temperature excursion was detected.

5. PLTEMP/ANL models

For the modeling with the PLTEMP/ANL code the 48-inch heated length was represented and the duct cross-sectional dimensions were made to match those of the experiments. The 48-inch heated axial length was divided into 24 two-inch axial layers. The chopped cosine axial power shape was represented. Both fuel plates were assumed to be identical and to have the same heat flux distribution. The lateral heat flux distribution was assumed to be uniform in all cases. The coolant inlet temperature and inlet and outlet pressures, the flow rate, and the total power were treated as known input quantities and were made to agree with those of the experiments. The code outputs were the outlet coolant temperature and the flow instability ratio, $R/(\Delta Tc / \Delta Tsat)$.

The code uses SI units. Both experiments report all quantities in British unit except for power which was in kW. In order to be consistent with current scientific practice, in the comparisons of measured versus PLTEMP/ANL results we converted all units to SI.

Every unique set of onset of flow instability conditions in either the Croft or the Waters report was simulated with PLTEMP/ANL. Where duplicate tests were run or where more than one test lead to essentially the same set of conditions corresponding to the onset of flow instability, only one set of conditions was simulated with PLTEMP/ANL.

6. Comparison of PLTEMP predictions with Croft measurements

Tables 1, 2, and 3 provide the measured data and the corresponding PLTEMP/ANL predictions of coolant outlet temperature and flow instability ratio for the Croft tests with channel thicknesses of 0.054, 0.072, and 0.94 inches, respectively. The good agreement between the measured and the predicted coolant outlet temperature values is to be expected since the outlet temperature can be predicted from a simple energy balance. A small difference between a measure and a predicted outlet temperatures may be the result of a measured outlet temperatures not being precisely in agreement with that that would be predicted based on the other measured quantities. As can be seen, PLTEMP/ANL predicts flow instability ratios that are close to 1.0. The smallest three values are 0.912, 0.941, and 0.983. The largest four are 1.045, 1.062, 1.072, and 1.088. Thus, most of the values are within about 4% of 1.0, which corresponds to the onset of flow instability. The value of 0.912, for example, implies that PLTEMP/ANL is predicting that if the power input to the code is multiplied by 0.912, then the code would predict an FIR of 1, i.e., the onset of flow instability. To be precise the code should have been rerun at the implied reduced power and if this produced an FIR that is other than 1, then additional runs would be required until an FIR of 1 was obtained. Then the resultant PLTEMP/ANL power could be compared to the measured power. However, given the large number of tests to be analyzed and the potential for only small gain in precision that could be of little value in the current assessment, it was decided to run the code only once for each experiment and to record the FIR provided in the output.

Table 1. PLTEMP/ANL Predictions for Croft Tests with 0.054-inch Channel Thickness.

Test	Power, kW	Flow, kg/s	Pressure, bar		Temperature, C			Flow Instability Ratio
					Measured		PLTEMP	
			Inlet	Outlet	Inlet	Outlet	Outlet	
1BO-5S	246 (397)*	0.424	19.37	15.58	54.4	189.4	190.3	0.985
3BO-5S	179 (289)	0.462	9.58	5.86	55.0	148.3	146.6	1.033
5BO-5S	181 (292)	0.312	17.37	15.65	55.0	189.7	190.9	0.983
6BO-5S	390 (630)	0.704	24.89	16.06	55.0	189.7	185.0	1.036
7BO-5S	132 (213)	0.393	18.20	15.65	115.0	195.6	193.0	1.006
8BO-5S	224 (362)	0.402	18.41	15.65	55.6	191.7	186.3	1.018

*The numbers in parentheses are the average heat flux over the heated areas, W/cm^2.

Table 2. PLTEMP/ANL Predictions for Croft Tests with 0.072-inch Channel Thickness.

Test	Power, kW	Flow, kg/s	Pressure, bar		Temperature, C			Flow Instability Ratio
					Measured		PLTEMP	
			Inlet	Outlet	Inlet	Outlet	Outlet	
1BO-2S	396.0 (639)*	0.723	21.03	15.65	53.3	180.6	182.0	1.023
3BO-5S	287.0 (463)	0.747	11.10	5.93	56.1	147.2	146.9	1.009
5BO-3S	286 (462)	0.548	18.48	15.65	57.8	181.1	180.3	1.042
6BO-3S	286 (462)	0.517	18.55	15.65	51.7	181.1	181.7	1.023
7BO-2S	509 (822)	0.965	24.82	15.65	55.6	181.7	179.6	1.045
9BO-2S	392.0 (633)	0.713	22.41	17.37	55.6	185.0	184.6	1.039
11BO-2S	437 (706)	0.722	20.68	15.65	38.3	180.0	180.8	1.018
12BO-3S	251 (405)	0.716	20.55	15.65	110.0	190.6	191.5	0.993

*The numbers in parentheses are the average heat flux over the heated areas, W/cm^2.

Table 3. PLTEMP/ANL Predictions for Croft Tests with 0.094-inch Channel Thickness.

Test	Power, kW	Flow, kg/s	Pressure, bar		Temperature, C			Flow Instability Ratio
					Measured		PLTEMP	
			Inlet	Outlet	Inlet	Outlet	Outlet	
1BO-2S	541 (873)*	1.033	22.27	15.65	54.4	177.8	177.5	1.028
2BO-5S	388 (626)	0.955	12.82	5.65	55.6	150.6	151.6	0.912
3BO-1S	387 (625)	0.973	13.03	6.55	53.9	148.9	147.9	1.000
4BO-1S	387 (625)	0.973	13.03	5.72	55.0	148.3	149.1	0.941
5BO-1S	388 (626)	0.738	20.27	15.65	54.4	180.0	177.9	1.025
6BO-5S	388 (626)	0.699	19.24	15.65	51.1	176.1	181.5	0.992
7BO-5S	387 (625)	0.748	19.99	15.86	50.6	171.7	172.3	1.071
8BO-1S	388 (626)	0.786	20.13	15.65	58.3	173.3	174.3	1.062
9BO-1S	388 (626)	1.023	15.17	7.58	55.6	145.6	145.3	1.088
10BO-4S	388 (626)	1.023	14.13	6.69	57.8	147.2	147.5	1.019

*The numbers in parentheses are the average heat flux over the heated areas, W/cm^2.

7. Comparison of PLTEMP predictions with Waters measurements

Tables 4 and 5 provide the measured data and the corresponding PLTEMP/ANL predictions of coolant outlet temperature and flow instability ratio for the Waters tests. Tables 4 and 5 respectively are for the tests with uniform and non-uniform power generation rate distribution along the width of the channel. In Table 4 the values of FIR range from 0.938 to 1.002. Thus, for the channel with the uniform power distribution across the width, PLTEMP/ANL is predicting flow instability to occur at powers levels that are between 6.2% below and 0.2% above those that were measured by Waters.

Table 4. PLTEMP/ANL Predictions for Waters Tests with Uniform Lateral Heat Flux.

Test	Power, kW	Flow, kg/s	Pressure, bar		Temperature, C			Flow Instability Ratio
					Measured		PLTEMP	
			Inlet	Outlet	Inlet	Outlet	Outlet	
U141	14.4 (12)*	0.048	2.77	2.72	54.4	130.6	125.6	0.968
U149	20.5 (17)	0.071	2.78	2.69	54.4	132.2	122.9	1.002
U156	27.0 (22)	0.092	2.80	2.69	54.4	130.6	123.9	0.988
U166	36.2 (29)	0.070	11.39	11.34	54.4	176.1	175.3	0.985
U173	51.4 (41)	0.100	11.42	11.34	54.4	176.1	174.9	0.989
U180	37.5 (30)	0.054	25.16	25.13	54.4	217.8	215.0	0.962
U191	68.3 (55)	0.100	25.23	25.13	54.4	221.7	212.6	0.976
U204	472 (381)	0.760	19.99	17.55	54.4	201.7	199.6	0.949
U215	702 (567)	1.115	22.72	17.62	54.4	201.7	201.5	0.938
U222g	725 (585)	1.164	23.06	17.55	54.4	197.2	199.9	0.947

*The numbers in parentheses are the average heat flux over the heated areas, W/cm^2.

Table 5. PLTEMP/ANL Predictions for Waters Tests with Non-Uniform Lateral Heat Flux.

Test	Power, kW	Flow, kg/s	Pressure, bar		Temperature, C			Flow Instability Ratio
					Measured		PLTEMP	
			Inlet	Outlet	Inlet	Outlet	Outlet	
N261	68.0 (55)*	0.125	25.30	25.20	54.4	181.7	181.9	1.212 (0.993)**
N271	27.4 (22)	0.108	2.88	2.79	54.4	116.1	114.8	1.154 (0.946)
N306	702 (567)	1.351	24.37	17.48	54.4	178.3	176.6	1.126 (0.923)
N314	470 (379)	0.909	20.58	17.55	54.4	177.8	176.0	1.133 (0.929)
N324	850 (686)	1.613	27.03	17.55	54.4	177.8	178.4	1.111 (0.911)
N335	720 (581)	1.401	24.37	17.41	54.4	176.1	175.3	1.136 (0.931)
N342	770 (622)	1.401	24.44	17.55	54.4	172.2	183.5	1.067 (0.875)
N346	660 (533)	1.264	23.13	17.55	54.4	174.4	177.2	1.122 (0.920)

*The numbers in parentheses are the average heat flux over the heated areas, W/cm^2.
**The value in parentheses is the flow instability ratio divided by 1.22.

The PLTEMP/ANL results of Table 5 show very high flow instability ratios ranging from 1.067 to 1.212 because the analysis ignored the non-uniform power distribution along the width and used the average power along the width. For safety analysis we would take a conservative approach. Typically, in the neutronics calculations the fueled width is divided into about five or 10 strips of equal width and the power of each strip is provided. In the PLTEMP/ANL analysis the power of the strip with the highest power is assume to apply to each of the strips. For example, if the heated width were divided into 10 equal strips as is assumed in Figure 2, then in the PLTEMP/ANL analysis the power of the heated width would be increased by a factor of 1.22 (as is shown above the second purple bar in the figure) to correspond to the relative heat flux of the hottest strip. A factor of 1.22 increase in power would cause the bulk coolant temperature rise, ΔTc, to increase by essentially a factor of 1.22. Since the flow instability ratio is R/(ΔTc / ΔTsat), a 1.22 factor increase in ΔTc will divide the flow instability ratios shown in Table 5 by a factor of 1.22. This results in the values shown in parentheses, which range from 0.875 to 0.99. Thus, for safety analysis values reasonably close to but less than 1.0 would be predicted in each case. The bias toward values less than 1 is to be expected since heat transfer and mixing with adjacent strips will reduce the coolant temperatures in the hottest strip of the experiment.

8. Range of parameters in the Whittle and Forgan tests

Table 6 shows the range of parameters in the Whittle and Forgan tests. Most of the Whittle and Forgan tests were performed on a rectangular duct, with a uniform heat flux both axially and width-wise over the heated regions of the plates, and with upward flow.

Table 6. Range of Parameters of Whittle and Forgan Tests.

Parameter	Minimum	Maximum
Velocity, m/s	0.61	9.1
Inlet Temp., C	35	75
Heat Flux, W/cm^2	42	340
Exit Pressure, bar	1.17	1.72
Channel Thickness, in.	0.055	0.127
Heated length, in.	16	24
Geometry	wide slot & round tube	

9. Discussions and conclusions

Tables 1 through 5 and Reference 5 together show that the PLTEMP/ANL code can reasonably accurately predict the onset of flow instability for a wide range of channel pressures, temperatures, powers, and channel thicknesses for water cooled research reactors with closed rectangular channels. What was once called “autocatalytic vapor binding” is actually a form of flow instability that results from a minimum in the demand (or system resistance) curve, as shown in Figure 1, which, in turn, is brought about by sufficient subcooled nucleate boiling.

The three sets of independent tests with electrically heated channels have covered a wide range of conditions. Pressures have varied from 1.17 to 27.03 bar. The heated tests sections have had lengths from 16 to 48 inches. The channel thicknesses had values from 0.054 to 0.127 inches. Uniform heat fluxes have been used, as well as axially varying ones, and ones that varied both axially and across the width. The average heat flux varied from 12 to 873 W/cm^2.[b] The coolant inlet temperature varied from 35 to 115° C.

Olson[5] shows that the Whittle and Forgan relationship, as implemented in PLTEMP/ANL and with η = 32.5, predicts flow instability reasonably well for the tests conducted at ORNL and reported by M. Siman-Tov et al.[6,7] Olson indicates that these tests were conducted with geometries relevant to research reactor conversion studies with coolant exit pressures of 1.75 to 28.8 bar, and with heat flux from 70 to 1800 W/cm^2.

Since all, or virtually all, of the tests in heated channels are for two-sided heating, the instance of one sided may be a potential source of concern. This may be of particular concern for the MURR because one of the two end fuel plates in each assembly tends to have the highest heat flux of all of the fuel plates in the assembly. Reference 9 provided an interesting perspective with regard to channels with one-side heating. He suggested that a channel that is heated from two sides could be compared to a pseudo channel heat from two sides that is formed by putting together two identical channels that are each heated from one side and are half as thick as the corresponding channel with two-sided heating. Here it is assumed that the two-sided channel and the pseudo two-sided heated channel both have the same flow rate. The major difference between these two channels is the shape of the velocity profile from one heated side to the other. The pseudo one has a zero-velocity condition at the middle of the span between the two heated walls and a hydraulic diameter that his about half as big, due to the no-slip condition at the middle of the span. The bubbles that cause flow instability tend to originate on the heat surfaces where the thermal and hydrodynamic boundary layers for the pseudo channel should be vary similar to those for the channel that is heated from two sides. Moreover, the effect of the smaller hydraulic diameter for the channel heat from one side is included in equation (1), above, where it tends to reduce the allowed bulk coolant outlet temperature and channel power. Furthermore, Reference 3 included tubular channels heated from the outer perimeter in their flow stability experiments and showed that the equation (3) is applicable to this geometry as well. Thus, flow stability may not be strongly dependent on the shape or the configuration of the heated perimeter.

In conclusion, although there is no single test that by itself closely matches the limiting conditions in the MURR, the preponderance of measured data and the ability of the Whittle and Forgan correlation, as implemented in PLTEMP/ANL, to predict the onset of flow instability for these tests leads one to the conclusion that the same method should be able to predict the onset of flow instability in the MURR reasonably well.

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[b] For the Croft and Waters experiments the heat transfer area was taken to be twice the heated width of the plate (1.00 inches for Croft and 2.00 inches for Waters) times the heated length (48 inches).

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Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4842

www.anl.gov

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