ANALYSIS OF FLOW EXCURSION EXPERIMENTS RELEVANT TO RESEARCH REACTORS: REVISITED

A. P. Olson
RERTR Program*
Argonne National Laboratory
Argonne, IL USA 60439

Presented at the 2006 International Meeting
On Reduced Enrichment for Research and Test Reactors

October 29-November 3, 2006
Cape Town, South Africa

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. DE-AC02-06CH11357 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

*Work supported by the U. S. Department of Energy
National Nuclear Security Administration
Under Contract No. DE-AC02-06CH11357

ANALYSIS OF FLOW EXCURSION EXPERIMENTS RELEVANT TO RESEARCH REACTORS: REVISITED

A. P. Olson
RERTR Program, Nuclear Engineering Division, Argonne National Laboratory
9700 S. Cass Avenue, Argonne, IL 60439, USA

ABSTRACT

The margin to flow instability is an important measure for safe operation of research reactors. The PLTEMP/ANL V3.1 code now includes two correlations for predicting onset of excursive-flow instability that are based on flow instability experiments by Whittle and Forgan, and by M. Siman-Tov et al. The Siman-Tov test data, from the ANS Thermal-Hydraulic Test Loop at ORNL, cover power and flow conditions appropriate to high-powered research reactors. Both groups of experimentalists conducted a broad range of electrically heated single channel experiments over pressure, heat flux, coolant velocity, inlet temperature, and channel geometry relevant to research reactor conversion studies. This paper reports on computer simulation of many of these experiments in order to validate the methods used to predict onset of flow instability in the PLTEMP/ANL V3.1 code. The Whittle and Forgan data is statistically analyzed to find an appropriate bound for the flow instability parameter, η.

1. Introduction

PLTEMP [1] includes two correlations for predicting the onset of excursive-flow instability that are based on work by Whittle and Forgan (W&F) [2], and on work by M. Siman-Tov et al. [3, 4]. Both groups constructed a number of electrically heated test sections. The key dimensions of these test sections, and heat flux magnitudes, were similar to those of research reactors using plate-type fuels. For each test section, a series of pressure drop *vs*. mass flow rate values were measured. A characteristic minimum in the pressure drop *vs*. flow curve marked the onset of flow instability.

A total of 74 tests on rectangular channels were reported in [2]. Of these, 8 tests were illustrated graphically, showing the pressure drop minimum. Test section 1 was used for the first four shown. The axially flat heat fluxes used were: 104, 145, 184, and 250 W/cm^2. Test section 3 was used for the second set of four tests. The axially flat heat fluxes used were: 66, 177, 218, and 276 W/cm^2. All 8 of these tests have been analyzed using PLTEMP 3.0. Mass flow rates at the onset of flow instability were interpolated by hand from Figs. 4 and 5 of [2].

There is enough data provided in [2] to determine the mass flow rate at the pressure vs. flow minimum from other tabular data, for any of the other 66 tests. All outlet pressures were 17 psia (0.1172 MPa), at which T_{sat}=104.1 C. Inlet pressures were determined by adding the reported pressure drop to the outlet pressure. The mass flow rate m for any W&F test can be obtained from:

$$m = \text{power}\cdot \eta/[C_p\cdot(L_H/D_H)\cdot(\Delta T_c/\Delta T_{sat})\cdot(\Delta T_{sub0}/\Delta T_c)\cdot(T_{sat}-T_{in})] \text{ , where}$$

$$\Delta T_c/\Delta T_{sat} = (T_{out}-T_{in})/(T_{sat}-T_{in});\quad \Delta T_{sub0}/\Delta T_c = (T_{sat\,exit}-T_{out})/(T_{out}-T_{in})$$

The PLTEMP model consisted of a single heated plate, with a half-channel on either side. Knowing the heat flux and plate dimensions, the total power is readily determined. The coolant mass flow rate was input such that the measured mass flow rate was achieved. In each case, the input value of ETA (η) was set to the measured value determined in [2]. A second series of calculations used the recommended η = 32.5.

PLTEMP edits "MINIMUM FLOW INSTABILITY POWER RATIO," FIR. This ratio would be precisely 1.0 if the experiment was exact, and if the PLTEMP model also was exact. It is based on Whittle and Forgan's relation:

$$R = \frac{1}{1 + \eta D_H / L_H}$$

In this equation, D_H is the heated diameter of the channel and L_H is the heated length. The flow instability factor is η. Table 1 shows the results of the PLTEMP calculations. The average FIR is 1.10, which deviates from the expected 1.00. Why it is not closer is not clear, but there are a number of contributing factors:

1. Measurement errors in power and mass flow rate are likely to be about 5% each.
2. Some heat (about 1% estimated by W&F) is also generated in the edges of the channel, and it is not clear whether or not Ref. 1 includes that in the quoted heat flux.
3. Mass flow rate data are not directly provided. I interpolated the data from supplied graphs which should be accurate to about 1 or 2 %. The flow rates used were on average 2% larger than the W&F data directly compute, which would indicate on average a 1.02 ratio for FIR.
4. Ref. 4 concerns a similar code validation for RELAP5/3.2 against the W& F data, and against ORNL thermal hydraulic test loop data (THTL). They also show graphically how RELAP5/3.2 compares against the W&F pressure drop vs. mass flow data, re-plotted in kPa and kg/m^{2}s units. For the 8 cases studied with PLTEMP, the flow rate shown by [5] and accredited to their interpretation of W&F data is 5.3% high, which is consistent with my own interpretation.

Table 1. Computed Flow Instability Criterion at the Onset of Flow Instability

Heat flux w/cm^2	T_{out} C	$\Delta T_c / \Delta T_{sat}$	$\Delta T_{sub0}/\Delta T_c$	Flow Instability power Ratio (using measured η)	Flow Instability power Ratio (using η=32.5)	η ′ min.
104	94.57	0.805	0.2416	1.11	1.059	24.7
145	95.59	0.826	0.2104	1.07	1.033	21.8
184	94.17	0.797	0.2543	1.13	1.070	26.2
250	97.75	0.850	0.1767	1.04	1.004	19.1
66	96.29	0.840	0.1899	1.04	1.024	21.0
177	93.64	0.786	0.2715	1.12	1.094	29.7
218	92.51	0.763	0.3099	1.16	1.127	33.5
276	92.87	0.771	0.2973	1.15	1.116	32.2

$\Delta T_c / \Delta T_{sat} = (T_{out}-T_{in})/(T_{sat}-T_{in})$; $\Delta T_{sub0}/\Delta T_c = (T_{sat\ exit}-T_{out})/(T_{out}-T_{in})$

2. Statistical analysis of W&F rectangular channel data

The 74 measured values of η for rectangular channels were statistically analyzed using *Mathematica,* with the following results:

Mean value	= 24.93
Variance	=13.69
Standard Deviation	= 3.70
95% confidence interval of the mean	= (24.074, 25.788)
95% confidence interval of the variance	= (10.14, 19.49)

If there were an infinite sample of test data available, and the test data followed a normal distribution, then the probability P that η lies within a band centered on the mean value $P(a \leq X \leq b)$, is obtained from the normal distribution integrated over the interval from a to b. Using a=-1.96, b=1.96, one obtains $P(17.68 \leq X \leq 32.18) = 0.95$. But we do not have an infinite sample, and we do not know the true variance. The lack of this knowledge can be accounted for, but will broaden the result. It is necessary to switch to the Student "t" distribution for N-1 samples, where N=74. Then a=-1.993, b=1.993, and one obtains $P(17.56 \leq X \leq 32.30) = 0.95$. This upper bound of 32.30 is to be compared to the IAEA Generic 10 MW Reactor work prepared by INTERATOM [6] which quoted 32.5 for what appears to be the same statistical bound. INTERATOM used Safety Standards of the Nuclear Safety Standards Commission (KTA) number KTA 3101.1, "Design of Reactor Cores of Pressurized Water and Boiling Water Reactors," Part 1: Principles of Thermo-hydraulic Design (February 1980, but reaffirmed 12/85, 6/90, 6/95, 6/00. Section 5.2 of that document states: "For operating conditions in which a critical boiling condition should be excluded, the minimum allowable margin to the critical boiling condition shall be specified in such a way that there is a 95% probability that at least 95% of the fuel rods concerned are protected from film boiling or dry-out."

Since we are most concerned when the true η could be larger than we have estimated, rather than smaller, it is better to compute the single-sided limiting probability $P(X < 0.95)$. This is because the FIR computed by PLTEMP is smaller for larger input ETA. If the supplied ETA is too small, the computed margin of safety implied by the FIR will be non-conservative. For comparison, from the normal distribution using $a = -\infty$, $b = 1.64$ yields $P(\eta < 30.998) = 0.95$. But using the Student "t" distribution, using $a = -\infty$, $b = 1.666$, yields $P(\eta < 31.09) = 0.95$. This yields a 95% confidence interval that 95% of the *rectangular channel* data measured by future measurements will not exceed 31.09.

We recommend that the limiting value for ETA be 32.5, consistent with the IAEA recommendation, even though it is more conservative than the value of 31.09 that is computed above.

3. World data on flow instability

Duffy and Hughes [7] in 1991 prepared a table of world data on flow instability measurements. It includes bundle data as well as channel or tube data. Duffy and Hughes also attempted to show the parametric dependences of flow instability measurements, and gave various predictive equations for the minimum mass flux at onset of flow instability. I have tried a number of their equations (17, 18, 26), finding very poor agreement with the W&F data. The trends look good, but the magnitudes are very far off.

4. Comparisons with the thermal-hydraulic test loop (THTL)

M. Siman-Tov et al. [3, 4] conducted experiments that were very similar to those of Whittle and Forgan. The THTL heated channel dimensions were very close to those of W&F (1.27 mm channel gap and 12.7 or 25.4 mm channel width, by 507 mm heated length), but the pressures and coolant velocities extended much higher (0.175 MPa-2.84 MPa exit pressure; 2.8-28.4 m/s exit velocity). The tests were conducted with light water in up-flow, with most cases using an inlet temperature near 45 C. The heat flux range was 0.7-18 MW/m^2. In addition to determining the pressure drop minimum at the onset of flow excursion, some of these tests also continued on to actual critical heat flux conditions. The axial power profile depends upon the resistivity of the aluminum heater, which varies with temperature. Consequently the axial power profile is not quite flat, but peaked toward the exit with a peak/average heat flux ratio of 1.07. The measured axial heat flux profile as shown in Fig.1 was modeled in the PLTEMP calculations. Also shown in Fig. 1 is a highly-peaked axial profile more like a case with control rods half-inserted, having a peak/average ratio of 1.474. Results obtained using this second profile will be discussed below.

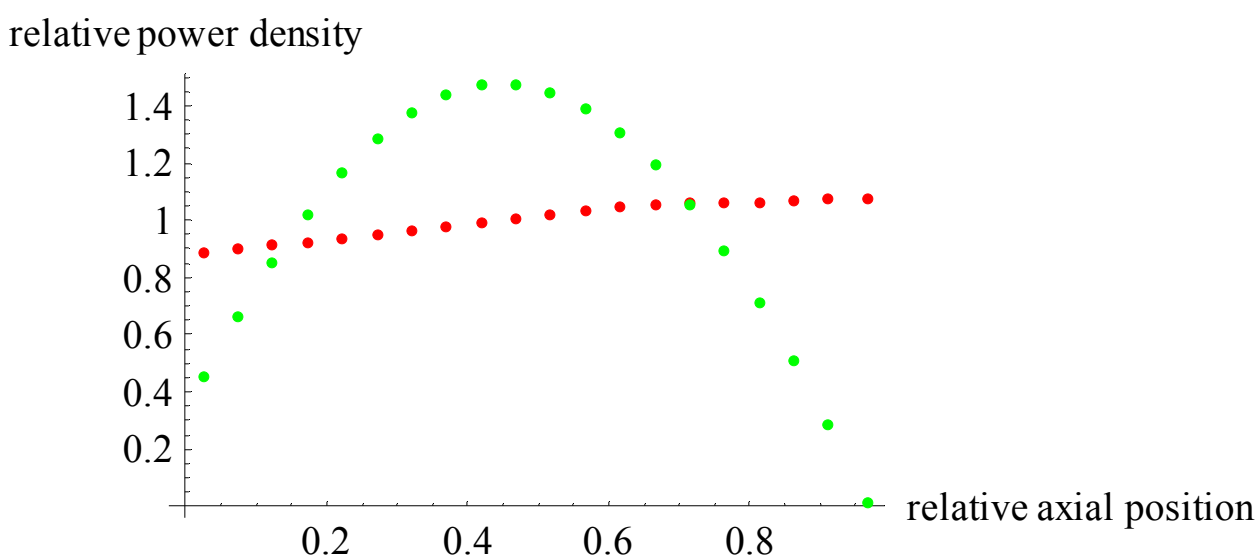

Fig. 1. THTL Axial Power Profile (inlet at x = 0)

Table 1 of [3] provides sufficient information with which to model the tests in PLTEMP. The ORNL Advanced Neutron Source Reactor design team proposed the following correlation, which is a modification of the Saha-Zuber correlation [8]:

$$St = q / (G\, C_p\, \Delta T_{sub}) = 0.0065 \qquad Pe > 70{,}000, \text{ Saha-Zuber}$$

$$St = q / (G\, C_p\, \Delta T_{sub}) = 0.0065\, \eta_{sub} \qquad Pe > 70{,}000, \text{ ORNL ANSR}$$

Where $\eta_{sub} = 0.55 + 11.21/\Delta T_{sub}$ is the proposed sub-cooling correction factor. The Stanton number is much better fitted at low exit sub-cooling (i.e. less than 20 C) by the ORNL ANSR modification. This new correlation was added to the edits from PLTEMP 3.0 as a Flow Excursion Ratio, FER. It is the minimum ratio of predicted excursion heat flux to actual flux, at all axial nodes and all heated surfaces.

Table 2 gives some results for tests carried out in the THTL that went beyond the minimum in the flow/pressure drop curve, to critical heat flux and burnout—even to melting of portions of the test section. The predictive ratios FIR and FER calculated by PLTEMP show their ability to predict these severe cases. A successful prediction requires that FIR< 1. or FER< 1.

Table 2. THTL Critical Heat Flux Tests

Test	q, w/cm^2	ONBR	W&F FIR†	ORNL FER	Pe	q/(Tsat-Tb) kW/m^2-s	V_{exit}, m/s
CF115B	1280	0.64	0.919	0.44	232000	2248	16.65
CF328A	1260	0.64	0.918	0.43	187000	1929	13.42
CF622B	610	0.63	0.919	0.41	208000	2435	14.99
FE212A	1260	0.67	0.968	0.6	242000	1045	17.21
FE318B	214	0.74	0.972	0.74	56900	253.6	4.21
FE331A	1210	0.71	1.028	0.76	235000	615.7	17.54

† η=32.5

As can be seen in Table 2, the W&F prediction is correct for 5 of 6 cases, and is only off by 2.8% in the one test slightly missed. On the other hand, the ORNL FER is correct in all 6 cases.

Table 3 is a series of tests that looked for the pressure drop minimum to mark the onset of flow excursion. It shows that the W&F FIR averages out to 1.073. This means that it predicts onset of flow excursion at an average of 7.3% higher heat flux than actually measured. It is therefore not conservative, but only by a small margin. It is worth noting that the FIR is quite a good measure for any flow velocity in the tested range. Table 3

also shows that the ORNL FER averages out to 0.936, while correctly predicting flow excursion for 8 of the 10 cases. It is worth noting that the FER does poorest at the lowest exit velocity tests with the lowest heat fluxes, where the criterion that the Peclet number should exceed 70,000 is not met. It does well for high-velocity tests of interest for the ANSR.

Table 3. THTL Flow Excursion Tests

	q, W/cm^2	ONBR	W&F FIR†	FER	Pe	q/(Tsat-Tb) kW/m^2-s	V_{exit}, m/s	η′ minimum
CF115B	1180	0.72	1.044	0.81	232000	544.6	17.27	29.5
CF328A	1250	0.74	1.076	0.9	249000	491.6	18.6	35.3
CF622A	650	0.71	1.042	0.79	247000	601.1	18.42	28.6
FE212A	1260	0.72	1.045	0.81	248000	578.2	18.49	29.7
FE318B	220	0.8	1.062	1.01	61700	135.5	4.54	32.2
FE331A	1220	0.75	1.117	0.97	250000	446.4	18.71	39.3
FE620B	540	0.74	1.022	0.73	82000	231.4	6.12	24.7
FE713B	80	0.92	1.178	1.68	37800	49.8	2.7	53.1
FE511C	1900	0.71	1.065	0.83	328900	741.4	24.6	30.6
FE712B	190	0.8	1.075	0.83	37000	83.4	2.77	31.0

† η=32.5

Figure 2 shows the W&F test data and THTL test data as computed by PLTEMP. Clearly there is a smooth parametric dependence on exit coolant velocity that is not quite linear. And clearly the parameter group q/(Tsat-Tb) in kW/m^2-s captures much of the systematic effects over the computed parameter ranges.

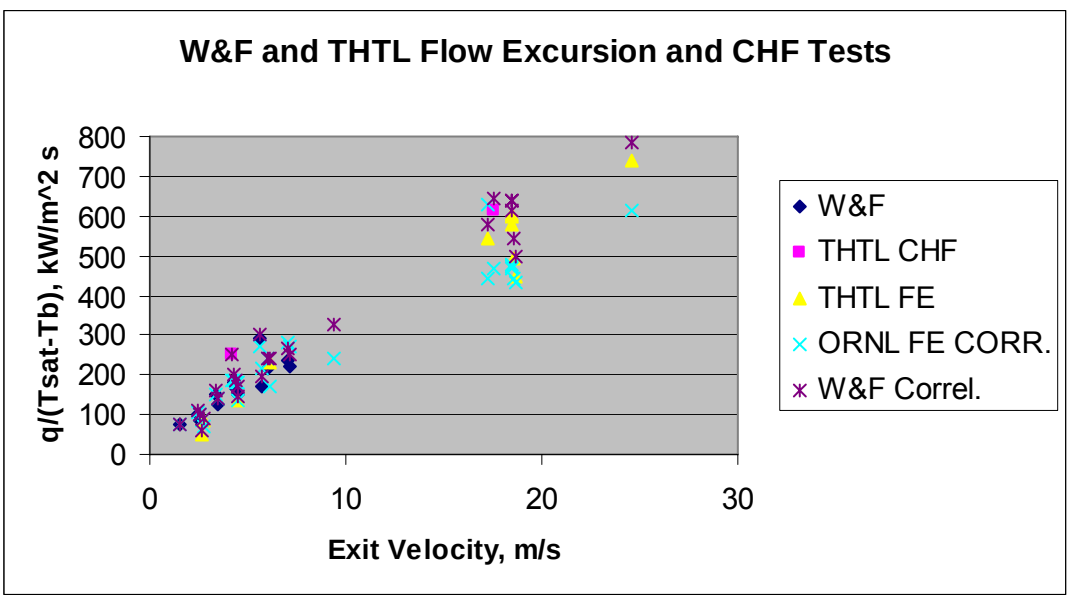

Fig. 2. Comparison of CHF and Flow Excursion Test Data with Correlations

The right-most column of Table 3 lists the minimum value of η′ which was obtained by PLTEMP using the local heat flux. This value should be larger than 32.5 to be indicative of stability. One can see that test FE713B somehow is not properly predicted by any of FIR, or FER, or the η′ method. The other flow excursion tests are predicted fairly well, in that 7 of 10 are predicted to be unstable and the other 3 are close to instability. The η′ measure is not linear with power, so a value of 53.1 definitely cannot be interpreted as requiring 32.5/53.1 less power to achieve the edge of stability.

4.1 Effect of Axial Power Peaking on Stability Predictions

As an example, THTL case CF115B (flow excursion test) was examined for a range of powers in order to predict the precise power where a given predictor would become 1.000. Fig. 3 shows the base condition, which uses the experimentally measured axial power profile (peak/average = 1.07). Fig. 4 shows the same PLTEMP case, but modified to have an axial power profile with a peak/average of 1.474, peaked toward the inlet. This case is similar to one with control rods half inserted. It was created by using a difference of sin(θ) and cos(θ) terms with the cosine weighted by 0.7.

It is clear that the W&F FIR is non-linear, and in fact yields the same predicted power ratio of 1.046. In other words, running the PLTEMP case with power scaled by a factor of 1.046 would yield FIR of 1.000. It is also clear that the ORNL FER is fairly linear, predicting a power scale factor of 0.938 for the base case and 1.028 for the peaked case. The peaked case would be permitted to run at 1.028/0.938 or 9.6% higher power than would the base case. This is because the correlation accounts for axial heat flux variation, and because the peak axial heat flux occurs well away from the channel exit. For the IAEA η′/32.5 measure, which also accounts for the local axial heat flux, the base power factor of 0.984 becomes 1.084 when highly peaked. The peaked case would be permitted to run at 1.084/0.984 or 10.2 % higher power than would the base case. Finally, one can see that the ORNL FIR and the IAEA η′ measure both account for the axial power profile in quite similar ways, while the W&F FIR correlation only considers coolant channel exit conditions. It is interesting to note that accounting for a strong axial peaking by these two methods indicates a higher predicted power for onset of flow excursion than the simpler W&F method yields.

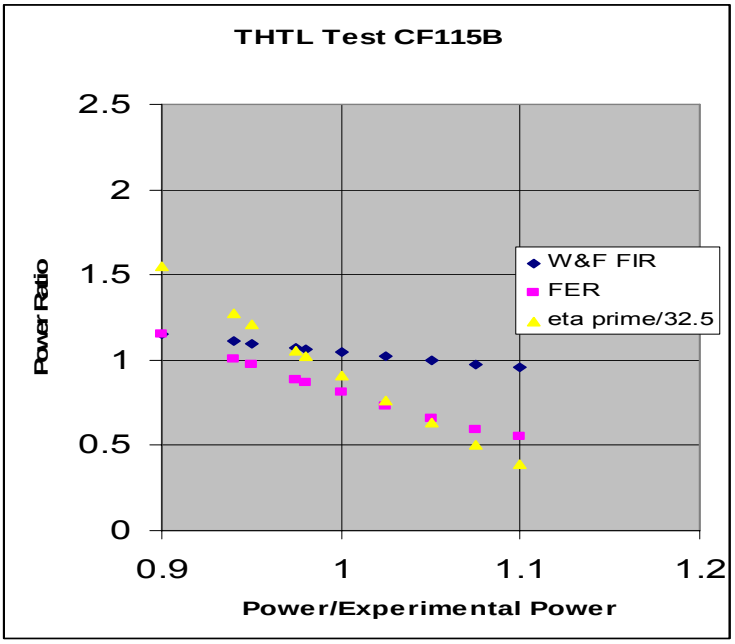

Fig. 3. Variation of Predictive Power Ratios FIR, FER, and η′/32.5 Near Instability: Base Axial Power Profile

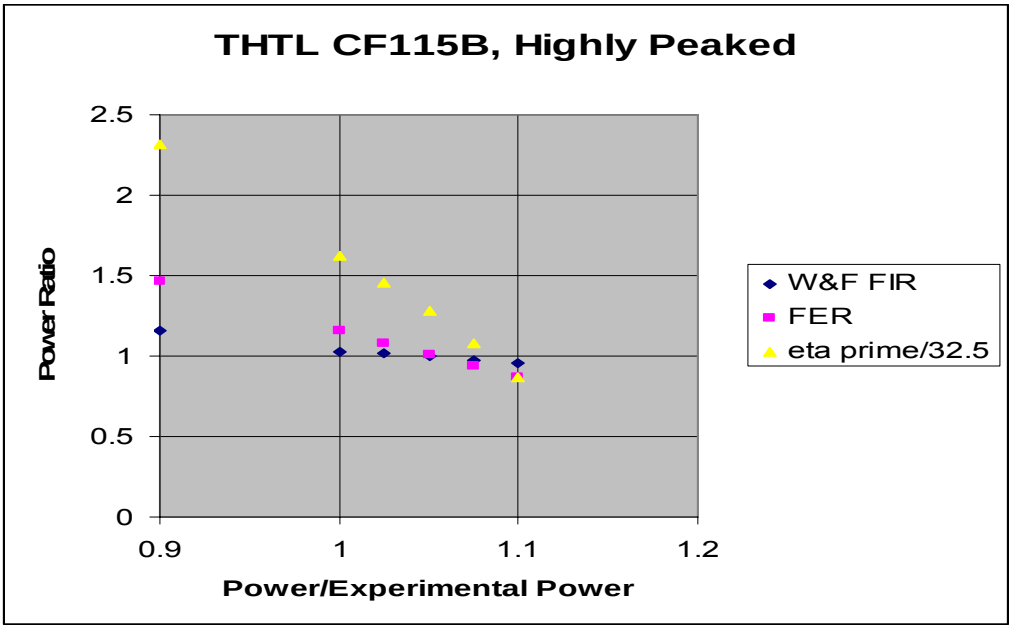

Fig. 4. Variation of Predictive Power Ratios FIR, FER, and η′/32.5 Near Instability: Highly Peaked Axial Power Profile

5. Conclusions

The remaining 8% error in mass flow rate falls within the measurement errors of the W&F experiments. Consequently the PLTEMP FIR for these 8 cases correctly represents the prediction of the onset of flow instability.

1. PLTEMP also computes a local value of η' on all heated surfaces. The code edits the minimum value of η'. From Table 1, the average minimum computed value of η' is 26.0 and an average measured value is 26.2. The very close agreement confirms that the computed η' is a valid measure of the onset of flow instability for channels with two-sided heating. As an example, Figure 5 shows the axial distribution of η' computed by PLTEMP for one of the cases examined. The η' appears to be of value for assessing highly peaked axial power profiles because it includes the effect of local heat flux while the W&F FIR does not.

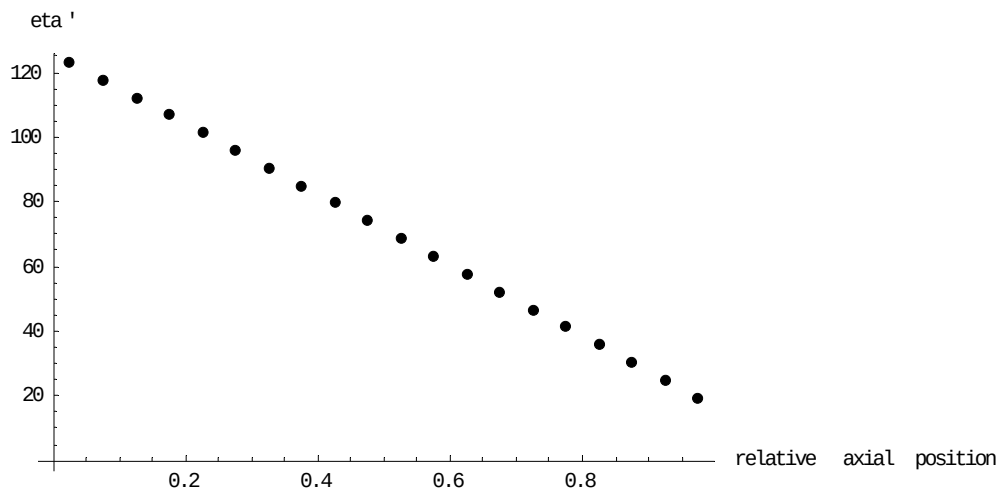

Fig. 5. PLTEMP Computed $\eta' = V\Delta T_{sub0}/q$ for W&F Test Section 1: 250 w/cm^2 Flat Power Profile

2. It is unclear at this time what validity, if any, these two measures of flow instability have for channels with heating on only one side. The theory takes into account the heated length and heated hydraulic diameter, so it in principle should be correct. The analyst must keep in mind that the W&F measurements span $83 < L_H/D_H < 191$. We have no data for one-sided heating.

3. The IAEA limiting value for η of 32.5 based on W&F data is close enough to my own statistical analysis result that we can use it in RERTR for the same purpose of establishing a baseline for rectangular channels.

4. The Duffy and Hughes parametric equations show trends only. They have poor predictive value as limits on mass flux at the onset of flow instability.

5. The W&F data are mostly for a flat power profile. Some tests (section 1A) used a profile that was flat over the inlet half, falling linearly to 68% at the exit. This shape has an axial peak/average ratio of about 1.09. It shows onset of flow instability very similar to the flat axial profile measurements. Reactor conditions with a highly-peaked axial profile will push the simple W&F method, such that an additional measure of conservatism should be applied.

6. The ORNL FER is excellent as a flow excursion predictor for high-velocity, high heat flux conditions as needed to design the ANSR. It should also apply well to axially peaked power profiles, as it is not a global measure like the W&F FIR.

7. The W&F FIR performs very well even for the high-velocity and high heat flux conditions examined by the THTL experiments. It seems to be more consistent than the FER as other test conditions change (geometry, pressure, sub-cooling). Using η=32.5 performs very well indeed. Unfortunately there are no measured data with a highly-peaked axial profile, which should show how the W&F FIR may become less accurate under that condition.

References

1. A. P. Olson, "The PLTEMP V2.1 Code," Proc. 2003 International Meeting on Reduced Enrichment for Research and Test Reactors, Chicago, Illinois, October 5-10, 2003.
2. R. H. Whittle and R. Forgan, "A Correlation for the Minima in the Pressure Drop Versus Flow-Rate Curves for Sub-Cooled Water Flowing in Narrow Heated Channels," Nuclear Engineering and Design 6, pp. 89-99 (1967).
3. M. Siman-Tov, D. K. Felde, G. Farquharson, J. L. McDuffee, M. T. McFee, A. E. Ruggles, M. W. Wendel, and G. L. Yoder, FY 1995 Progress Report on the ANS Thermal-Hydraulic Test Loop Operation and Results, ORNL/TM-12972, Oak Ridge National Laboratory (July 1997).
4. M. Siman-Tov, D. K. Felde, J. L. McDuffee, and G. L. Yoder, Experimental Study of Static Flow Instability in Sub-cooled Flow Boiling in Parallel Channels, 4th ASME/JSME Thermal Engineers Joint Conference, Maui, Hawaii, CONF-950113- -1,Oak Ridge National Laboratory (January 1995).
5. Tewfik Hamidouche and Anis Bousbia-salah, "RELAP5/3.2 Assessment Against Low Pressure Onset of Flow Instability in Parallel Heated Channels," Annals of Nuclear Energy 33, pp. 510-520 (2006).
6. INTERATOM, on behalf of the Minister of Research and Technology of the Federal Republic of Germany, Appendix A-1 of IAEA-TECDOC-643, "Research Reactor Core Conversion Guidebook," Vol. 2: Analysis (Appendices A-F), International Atomic Energy Agency, Vienna, (April 1992).
7. R. B. Duffey and E. D. Hughes, "Static Flow Instability Onset in Tubes, Channels, Annuli, and Rod Bundles," Int. J. Heat Mass Transfer Vol. 34, No. 10, pp. 2483-2496 (1991).

8. P. Saha and N. Zuber, Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling, *Proceedings of the 5th International Heat Transfer Conference*, Tokyo, **IV**, 175-179 (1974).