FUNDAMENTAL APPROACH TO TRIGA STEADY-STATE THERMAL-HYDRAULIC CHF ANALYSIS

E. E. Feldman
RERTR Program
Nuclear Engineering Division
Argonne National Laboratory
Argonne, IL USA 60439

ABSTRACT

Methods are investigated for predicting the power at which critical heat flux (CHF) occurs in TRIGA reactors that rely on natural convection for primary flow. For a representative TRIGA reactor, two sets of functions are created. For the first set, the General Atomics STAT code and the more widely-used RELAP5-3D code are each employed to obtain reactor flow rate as a function of power. For the second set, the Bernath correlation, the 2006 Groeneveld table, the Hall and Mudawar outlet correlation, and each of the four PG-CHF correlations for rod bundles are used to predict the power at which CHF occurs as a function of channel flow rate. The two sets of functions are combined to yield predictions of the power at which CHF occurs in the reactor. A combination of the RELAP5-3D code and the 2006 Groeneveld table predicts 67% more CHF power than does a combination of the STAT code and the Bernath correlation.

1. Introduction

TRIGA reactors that rely on natural convection for primary flow use vertically oriented fuel rods of diameter of about 37 mm. Each reactor is located near the bottom of a deep pool of water. These TRIGA reactors can be divided into three distinct groups, based on rod arrangement – hexagonal, circular, and rectangular. The reactors in the hexagonal group position all of the fuel rods on a uniform triangular pitch. The circular TRIGAs are similar to the hexagonal ones except that the rods are arranged in concentric circles about the center position. This causes the pitch to be non-uniform. The rectangular-pitch reactors were originally operated as Material Test Reactors (MTRs) with the fuel in plates and were converted to use TRIGA rods. Because TRIGA reactors may operate with subcooled nucleate boiling during normal operation, the margin to critical heat flux (CHF) can be a limiting design criterion. The purpose of this paper is to provide insight into the thermal-hydraulic analysis and the prediction of CHF for TRIGA reactors. An expanded report is planned.

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2. Coolant Flow Rate

The TRIGA rods are arranged in a tight, open lattice with pitch-to-diameter ratios typically less than 1.2. There are no devices to encourage cross flow among adjacent channels formed by the cusps of immediately adjacent rods. A reasonable model is one similar to Figure 1 in which each channel is treated as an isolated channel. This model is conservative because in the analysis the coolant in the channel with the hottest coolant is not cooled by exchanging coolant with it cooler neighbors or by conducting heat to other channels. Since this model treats the flow of each channel as being independent of its neighbors, only the potentially limiting channels need be considered.

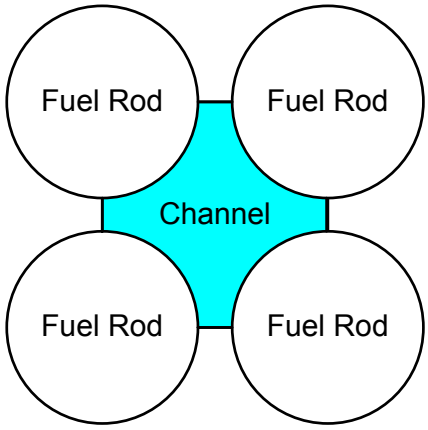

Figure 1. Coolant Channel

In the steady-state analysis of a single channel, if the channel flow rate is known, many other key thermal quantities can be easily deduced without the use of a sophisticated computer code. When the coolant inlet temperature to the channel and the axial power distribution along the channel are known, the mixed-mean coolant temperature, the enthalpy, and the quality at each axial level along the channel can be determined from an energy balance.

The determination of the flow rate in the limiting channel typically employs a computer code. These codes use coolant momentum equations in which the buoyancy forces are equated with the combination of the hydraulic resistance forces and the momentum flux (or acceleration) forces. The buoyancy forces are a result of the differences in coolant density. The hydraulic resistance has three components: an inlet resistance, an exit resistance, and friction along the vertical surfaces of the fuel rods. The inlet and outlet resistances are represented by form-loss (or, K-loss) factors.

Boiling considerably complicates the thermal-hydraulic analysis necessary to predict the channel flow. Any boiling, even subcooled boiling, greatly increases the frictional resistance to coolant flow along the vertical surfaces of the fuel rods. Increased boiling increases the frictional resistance and the vapor-induced voids. These voids produce greater buoyancy with which to drive flow. Thus, increased boiling produces opposing effects that can either increase or decrease flow. In a boiling channel, the vapor and the liquid need not move at the same speed. Thus, boiling is a complex phenomenon for which current modeling methods heavily rely on empirical correlations.

2.1 The STAT Code [1]

STAT is a proprietary code that was developed at General Atomics (GA) in San Diego, California specifically for the steady-state analysis of a single coolant channel of a TRIGA reactor. The code predicts the channel flow rate, the bulk coolant temperatures, the heat fluxes, and the CHF for the fuel rod surfaces. The code includes the effects of

subcooled boiling. The coolant channel is divided into a series of horizontal layers and solved one layer at a time, starting at the channel inlet. A feature of the code is its brief input. The code uses two correlations to provide two independent estimates of the CHF at each axial location of each fuel rod surface. The Bernath correlation [2] is the more limiting of the two for TRIGA reactor applications.

2.2 The RELAP5-3D Code [3] and Its Application to TRIGA Thermal-Hydraulic Analysis

RELAP5-3D is a general-purpose code capable of analyzing the transient coupled thermal, hydraulic, and neutronic behavior of light water nuclear reactors. It does not assume a prescribed geometry, but instead allows the user to connect a series of volumes of fluid nodes to each other to represent a channel or a series of connected channels and volumes. Solid structures can be attached to the boundaries of the fluid volumes to represent fuel elements. The only two CHF correlation options currently in the code are the 1986 Groeneveld CHF look-up table [4] and the PG-CHF CHF correlations [5],[6]. The current developer of the RELAP5 code, Idaho National Laboratory, is considering the inclusion of the 2006 Groeneveld CHF look-up table [7].

2.3 Comparison of STAT and RELAP5 Flow Results

GA provided sample input and output files and the FORTRAN source for the STAT code. Table 1 shows key representative thermal-hydraulic parameters for a hexagonal pitch and a rectangular pitch TRIGA reactor. These should not be considered to be the most limiting for safety analysis of any particular reactor. The axial power distribution for the hottest channel of the hexagonal pitch TRIGA is provided in Figure 2. Figure 3 provides a schematic view of the RELAP5 model used to represent a TRIGA coolant channel. The source and the sink are at the same elevation and pressure.

Table 1. TRIGA Generic Reactor Parameters

	Reactor	
Parameter	**Hexagonal Pitch**	**Rectangular Pitch**
Fuel element pitch	**Hexagonal**	**Rectangular conversion**
Flow area per rod, cm^2	**5.464**	**5.532**
Hydraulic diameter, mm	**18.64**	**19.65**
Rod (heated) diameter, mm	**37.34**	**35.84**
Inlet temperature, C (F)	**25 (77)**	**30 (86)**
Pressure (~mid-core), bars	**1.68**	**1.80**
Saturation temperature, C (F)	**114.8 (238.6)**	**116.9 (242.4)**
Inlet K-loss	**3.58**	**1.672**
Exit K-loss	**3.0**	**0.6**
Reactor power, MW	**2.0**	**1.0**
Number of rods	**100**	**90**
Radial power factor (hot. rod)	**1.5**	**1.565**
Power of hottest rod, kW	**30.0**	**17.4**

An important input parameter in the STAT code is the “void detachment fraction” (VDF). This quantity affects the buoyancy term in the hydraulics solution that is used to

determine the flow rate. For the current comparison the most conservative value for the VDF, 0, was used.

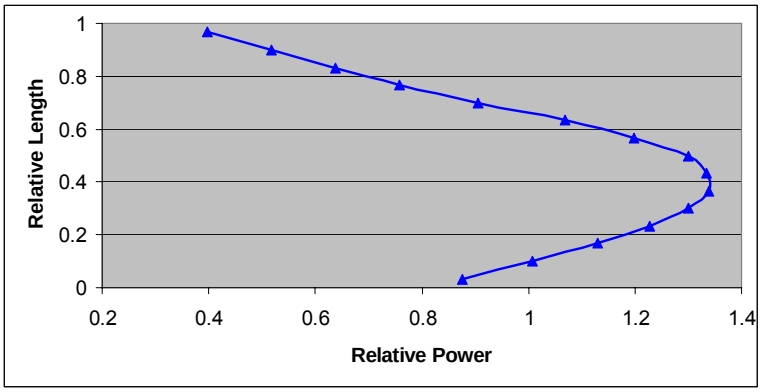

Figure 2. Axial Power Shape for the Hottest Channel of the Hexagonal Pitch TRIGA Reactor

Figure 4 provides a comparison of STAT and RELAP5 flow rate predictions for the hexagonal pitch TRIGA reactor. The vertical dashed line at 30 kW per rod corresponds to full power for the reactor. The specific calculated data points are shown on the graphs. The interior color of three symbols for the STAT code is shown in white to identify a warning provided with the solution. The code indicates that the results are suspect when the outlet coolant temperature is within 11° F (6.1° C) of the coolant saturation temperature. Thus, the relative maximum flow rate at about 33 kW/rod could be caused by a limit in the code being exceeded.

The maximum power for the RELAP5 prediction, 48 kW/rod, is the highest power for which a solution was obtained. RELAP5 finds steady-state solutions by solving a pseudo-transient in which there are no changes in the boundary conditions and forcing functions. An initial guess is the starting point. A steady-state solution is obtained when there are essentially no further changes in any dependent variable with time. At 48 kW/rod the pseudo-transient solution has permanent minor oscillations in the flow rate, which increases in amplitude as the power is increased. The cause of these oscillations could be physical or an artifact of the calculation.

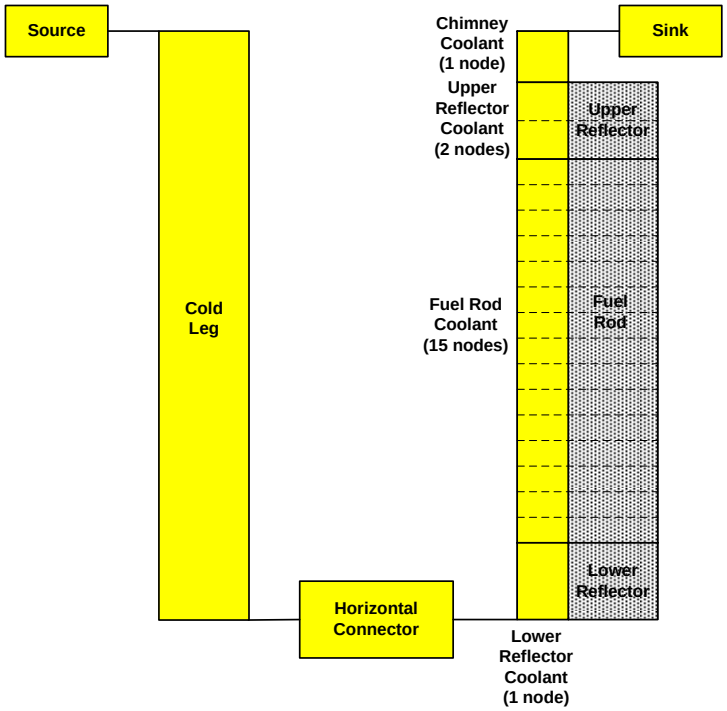

Figure 3. Schematic View of RELAP Model of TRIGA Coolant Channel

3. Critical Heat Flux Correlations

In general, published values of CHF are based on measurements made with a uniform heat flux over the length of the channel. Because nuclear reactors have heat fluxes that

vary along the lengths of the coolant channels, STAT and RELAP5 use the "direct substitution method" to adapt the CHF data that was measured with a uniform heat flux to the reactor situation. This method assumes that if a given set of pressure, mass flow rate, and quality/temperature values produced a particular value of CHF in the experiment, the same set of conditions at any location in the reactor will produce the same value of CHF. The ratio of the predicted CHF to the local value of heat flux in the reactor is defined to be the CHF ratio at that location. The power that causes the minimum CHF ratio among all locations to be 1.0 is the CHF power. TRIGA reactors typically operate at a pressure of about 1.8 bar and have a mass flux of about 100 kg/m^2-s at licensed power conditions. The mass flux is predicted to increase to values approaching 300 kg/m^2-s as CHF is approached.

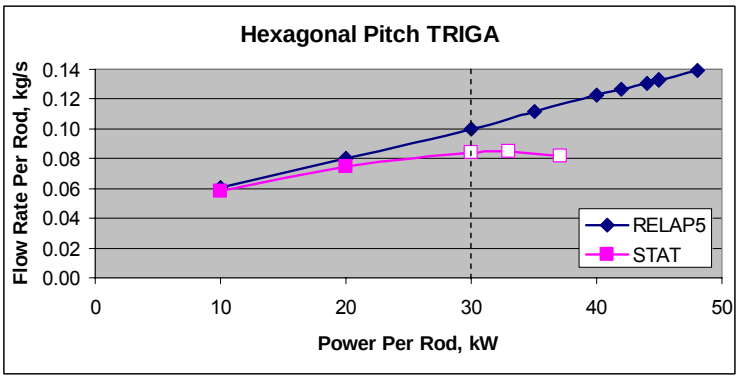

Figure 4. Comparison of the STAT and RELAP5 Flow Rates for the Hexagonal Pitch TRIGA Reactor

Hall and Mudawar of Purdue University have compiled and assessed the world's CHF data for water and have produced simple correlations for subcooled water flowing inside a tube that is heated from the outside. [8],[9] For applications where the axial distribution of heat flux is not uniform, they recommend their "outlet" CHF correlation, which is included in this study and referred to as the "Purdue" or the "Purdue outlet" correlation.

Groeneveld et al. attempted to collects the world's data for CHF in water and produced a CHF look-up table that they published in 1986. [4] This is a three-dimensional table that provides CHF as a function of pressure, mass flux, and quality for a round tube with an 8 mm inner diameter. The tube is heated from the outside and cooled at the inner surface. Linear interpolation is used to obtain CHF values corresponding to conditions between those listed in the table. For tube or hydraulic diameters other than 8 mm, a correction factor multiplier, K_1, is applied to the value obtained from the table. K_1 is given by $K_1=(8/D)^{1/3}$ for $2<D<16$ and $K_1=(8/16)^{1/3}=0.79$ for $D>16$, where D is the hydraulic diameter in mm. Other factors also multiply the table output. The two other K-factors that effect CHF for TRIGA reactors are K_2, which is a correction factor for rod bundles versus round tubes, and K_4, which is an entrance effect factor. Reference [10] revised K_1 to be $K_1=(8/D)^{1/2}$ for $3<D<25$ and $K_1=(8/16)^{1/2}=0.57$ for $D>25$. RELAP5 [3] uses the earlier version of K_1. Recently, the 2006 Groeneveld table was published. [7]

The PG-CHF correlations are based on three separate experimental databases – one for tubes, one for rod bundles, and one for annuli. For each of these three geometries there are four forms of the PG_CHF correlation – "Basic", "Flux", "Geometry", and

"Power". The rod bundle database is based on 153 test geometries and 7,616 data points. [5]

Figure 5 shows the Bernath, Groeneveld, and Purdue CHF values as a function of quality for a pressure typical of TRIGA reactors and a mass flux that is expected to be near CHF conditions. This comparison is for a uniformly heated 8-mm tube for which all of the Groeneveld K-factors are 1. Thus, the differences in the three Groeneveld curves are due solely to differences in the three Groeneveld tables. The Purdue curve ends at a quality of −0.05 because this is the limit of the correlation. Figure 6 shows a similar comparison with a tube diameter of 19.65 mm, which corresponds to the hydraulic diameter of the rectangular pitch TRIGA reactor described in Table 1. The increased separation between the 1986 Groeneveld curve and the 1995 and 2000 ones occurs because the 1986 curve used the earlier K_1 factor and the other two used the later one. In Figure 6, the leftmost 11.5° C temperature data points are at a quality of −0.05 and

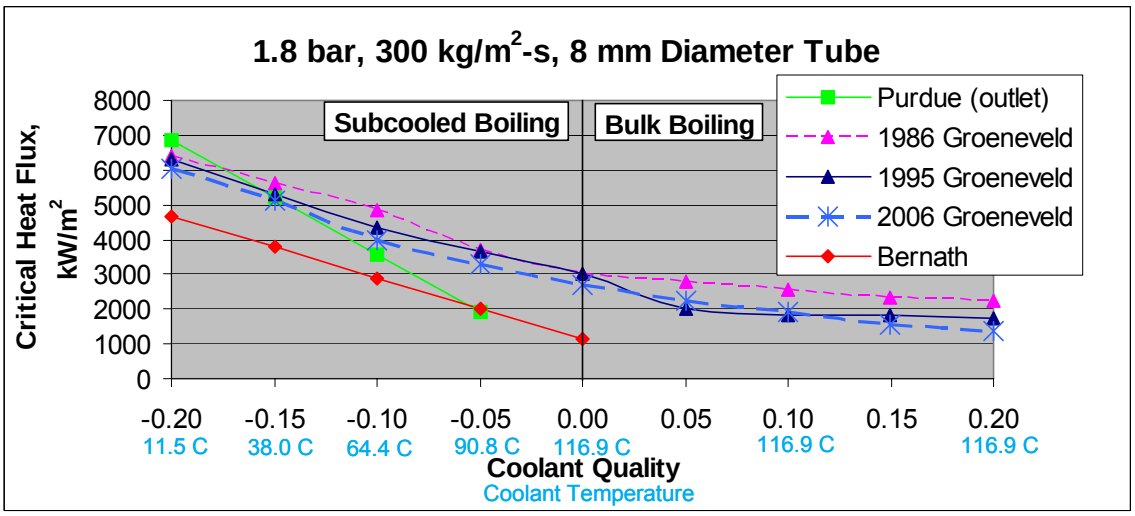

Figure 5. CHF vs. Quality for an 8 mm Diameter Tube

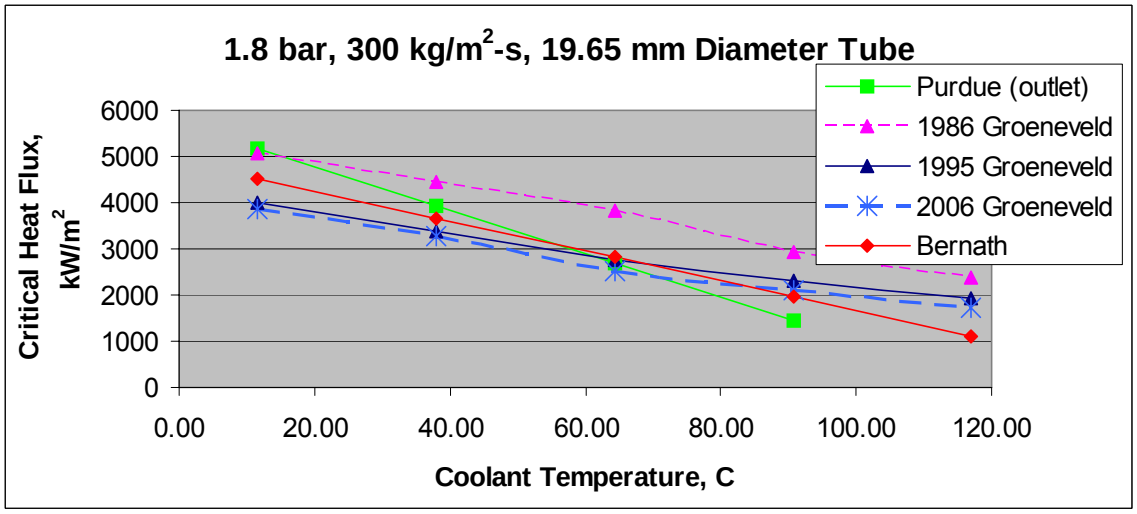

Figure 6. CHF vs. Temperature for a 19.65 mm Diameter Tube

the rightmost 116.9° C ones are at a quality of 0. The ones in between are at quality intervals of 0.05.

4. CHF Predictions for the Hexagonal Pitch TRIGA Reactor

The hottest channel in the hexagonal pitch TRIGA reactor was analyzed with the RELAP5 code at its nominal power of 30 kW per rod. The resultant thermal hydraulic conditions were used to predict the 2006 Groeneveld CHF at each axial level. The ratio of the CHF to the local heat flux at each level was used to create the blue curve with the round symbols in Figure 7. The other three axial distributions of CHF ratio in the figure were obtained in an analogous manner. Similar plots were created for the four PG-CHF rod-bundle correlations. It was observed that the minimum CHF ratio for the "power" version of PG-CHF was more than 50% greater than that for the other three PG-CHF curves. The curve on the far left shows the axial distribution of the K_4 Groeneveld factor. The CHF power for each plot is the product of its minimum CHF ratio and 30 kW/rod. However, as is well-known and demonstrated below, the flaw in this approach is that the CHF correlations are being evaluated at the nominal power of 30 kW/rod rather than at the power that corresponds to a minimum CHF ratio of 1.

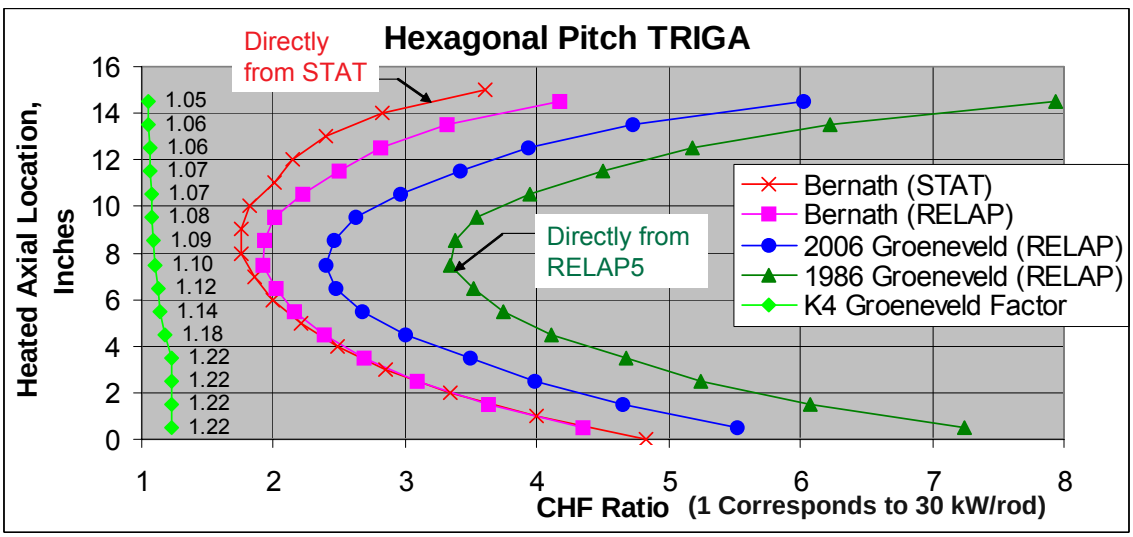

Figure 7. CHF Ratios for the Hexagonal Pitch TRIGA Evaluated at Nominal Power, where the Highest Power Rod is 30 kW

The shortcoming in the Figure 7 approach is overcome in Figure 8. The middle curve in the figure (diamond symbols) shows the predicted CHF power per rod for the limiting rod of the hexagonal pitch TRIGA reactor, based on the 2006 Groeneveld table. Each point of this curve was obtained, for each assumed flow rated and the 25° C inlet temperature given in Table 1, by adjusting the assumed power until the assumed power and the CHF power were equal. The required calculations were done by hand with the aid of a computer spreadsheet. The heated length was divided into 15 axial layers, as indicated in Figure 3. The bottom "RELAP5 Conditions" curve (triangle symbols) is the RELAP5 curve given in Figure 4. Since RELAP5 experienced flow oscillations starting

at 48 kW/rod, a linear extrapolation is used beyond this power in Figure 8. The power at the intersection of the extrapolated curve and the CHF power curve, 68.9 kW/rod, is the predicted CHF power for the limiting rod. A more conservative option would be to use the flow at 48 kW/rod instead of the one at the intersection. This produces a CHF power of 62.1 kW/rod.

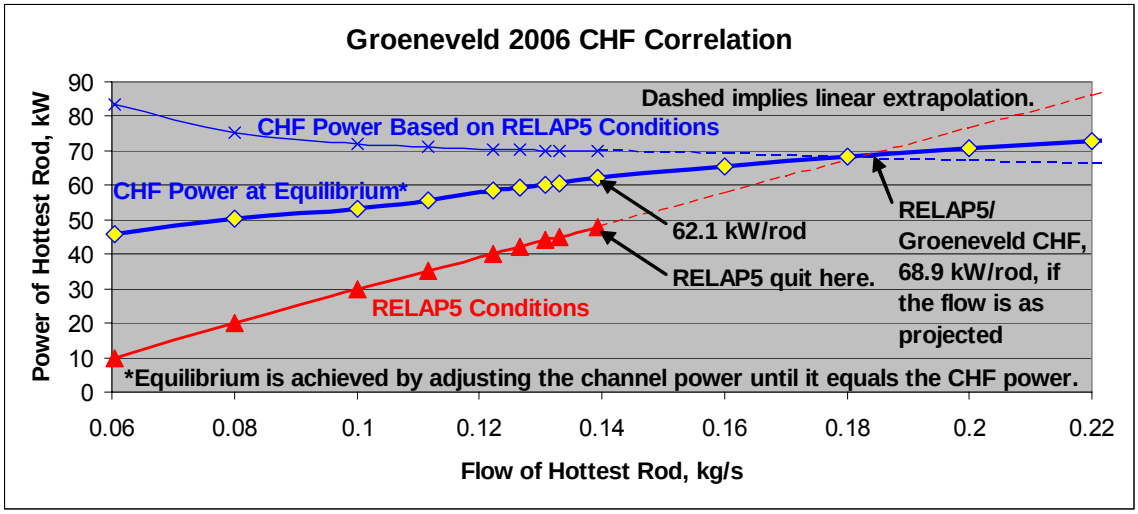

Figure 8. CHF Power of the Hexagonal Pitch TRIGA Reactor Based on the Groeneveld 2006 Table

The top curve in Figure 8 ("x" symbols), which is extrapolated for powers beyond 48 kW/rod, shows the CHF power that would have been predicted if at each flow rate the RELAP5 power is used to predict the CHF power. For example, for an assumed power of 30 kW/rod, RELAP5 predicted a flow rate of 0.1001 kg/s per rod. This combination of power and flow rate predicts a CHF power of 71.9 kW/rod, rather than the 53.3 kW/rod value of the middle curve. The ratio of 71.9 kW/rod and 30 kW/rod, 2.40, is the minimum CHF ratio provided in Figure 7 for the 2006 Groeneveld (RELAP) curve.

Curves analogous to the middle curve of Figure 8 were produced for the Bernath, Purdue, and PG-CHF correlations. Figure 9 shows most of these curves. The "flux" and "power" PG-CHF curves are coincident. The other two PG-CHF curves, which are not shown, are nearly coincident with the "flux" and "power" ones. The STAT predicted flow rate versus power relationship of Figure 4 and the RELAP5 one with its Figure 8 extrapolation are also shown in Figure 9. The intersection of either of these two curves with a CHF curve provides a prediction of CHF power, as indicated by the numbers in parentheses on Figure 9. The thick black straight dashed line in Figure 9, labeled "X_{exit}=0", shows the combinations of power and flow rate that produce a quality of 0 at the channel exit.

Table 2 summarizes all of the predictions of CHF power per rod for the limiting rod. Column A uses the maximum rod flow rate calculated by RELAP5 of 0.1394 kg/s. Column B uses the flow at the intersection of the CHF and RELAP5 or STAT curves.

Column C uses a power of 30 kW/rod and the flow rate that RELAP5 or STAT predicts for a power of 30 kW/rod.

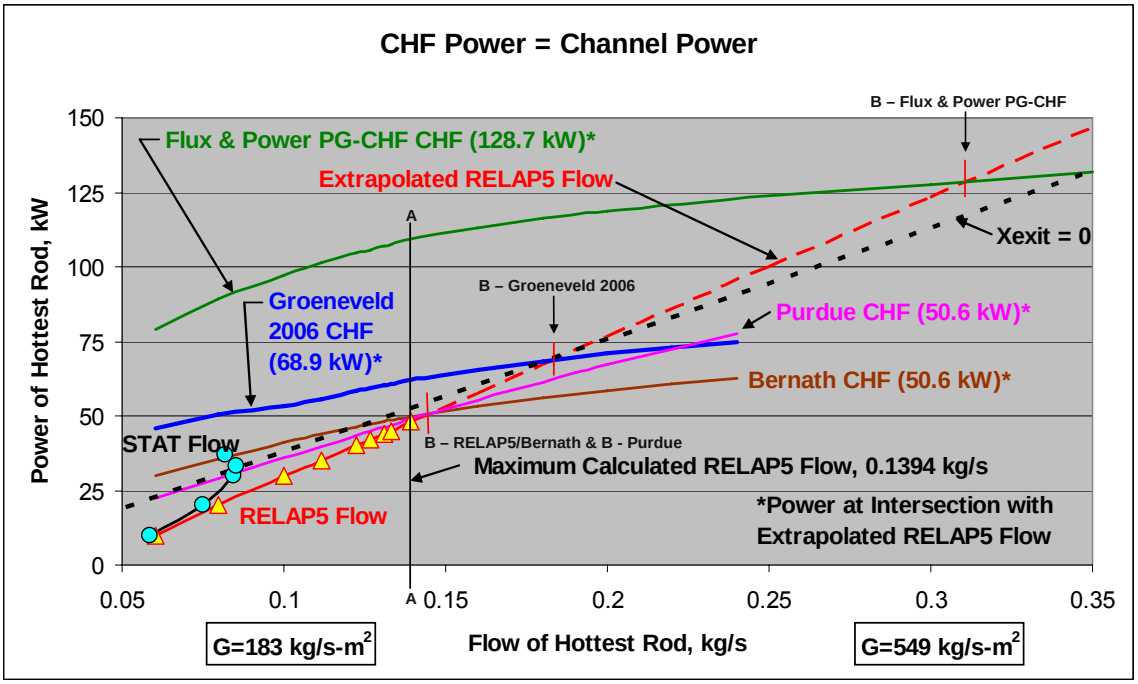

Figure 9. Comparison of the CHF Predictions for the Hexagonal Pitch TRIGA Reactor

Table 2. Summary of CHF Results for Hexagonal Pitch TRIGA Reactor

Flow	CHF Correlation	Rod CHF Power, kW			CHF Ratio*		
		A**	B+	C++	A**	B+	C++
STAT	Bernath		37.1	52.5		1.24	1.75
RELAP5	Bernath	49.6	50.6	57.5	1.65	1.69	1.92
	Purdue	48.9	50.6		1.63	1.69	
	Groeneveld 2006	62.1	68.9	71.9	2.07	2.30	2.40
	Groeneveld 1986			100.3			3.30
	PG-CHF, Basic	105.9	124.4		3.53	4.15	
	PG-CHF, Geometry	108.9	129.7		3.63	4.32	
	PG-CHF, Power or Flux	109.2	128.7		3.64	4.29	

***1.0 corresponds to 30 kW for the highest power rod and 2.0 MW for the reactor.**
****A (RELAP5 Flow): CHF curve at maximum calculated flow per rod (0.1394 kg/s, thin vertical black line A-A in Figure 9), where RELAP5 flow begins to oscillate.**
+B (Extrapolated RELAP5 Flow): Intersection of a CHF correlation curve and a reactor flow curve, as shown in Figure 9.
++C (Not Recommended): CHF based on calculated reactor power and flow at 30 kW/rod.

5. Discussion and Conclusions

The experimental data used to develop the Bernath, Purdue outlet, and PG-CHF rod bundle correlations do not match TRIGA reactor conditions near CHF. The 2006

Groeneveld correlation is judged to be the best choice for TRIGA reactors. It is the newest and incorporates the world's CHF data in water. In regions of the 2006 Groeneveld table where measured data is lacking, which include TRIGA CHF conditions, it makes use of CHF values predicted by CHF correlations, such as those provide by Hall and Mudawar [9]. Thus, some of the Purdue data is, in effect, included in the 2006 Groeneveld table.

In past safety analyses, the traditional manner of predicting CHF in TRIGA reactors was to use the GA STAT code, which employs the Bernath CHF correlation. For the hexagonal pitch TRIGA reactor this method predicts a CHF power of 37.1 kW/rod. The proposed method with the highest calculated RELAP5 flow (column A of Table 2) results in a 67%, i.e., (62.1/37.1 – 1) × 100%, increase in the predicted CHF power for the hexagonal pitch TRIGA reactor and a 25%, i.e., (62.1/49.6 – 1) × 100%, increase relative to RELAP5/Bernath combination of column A.

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