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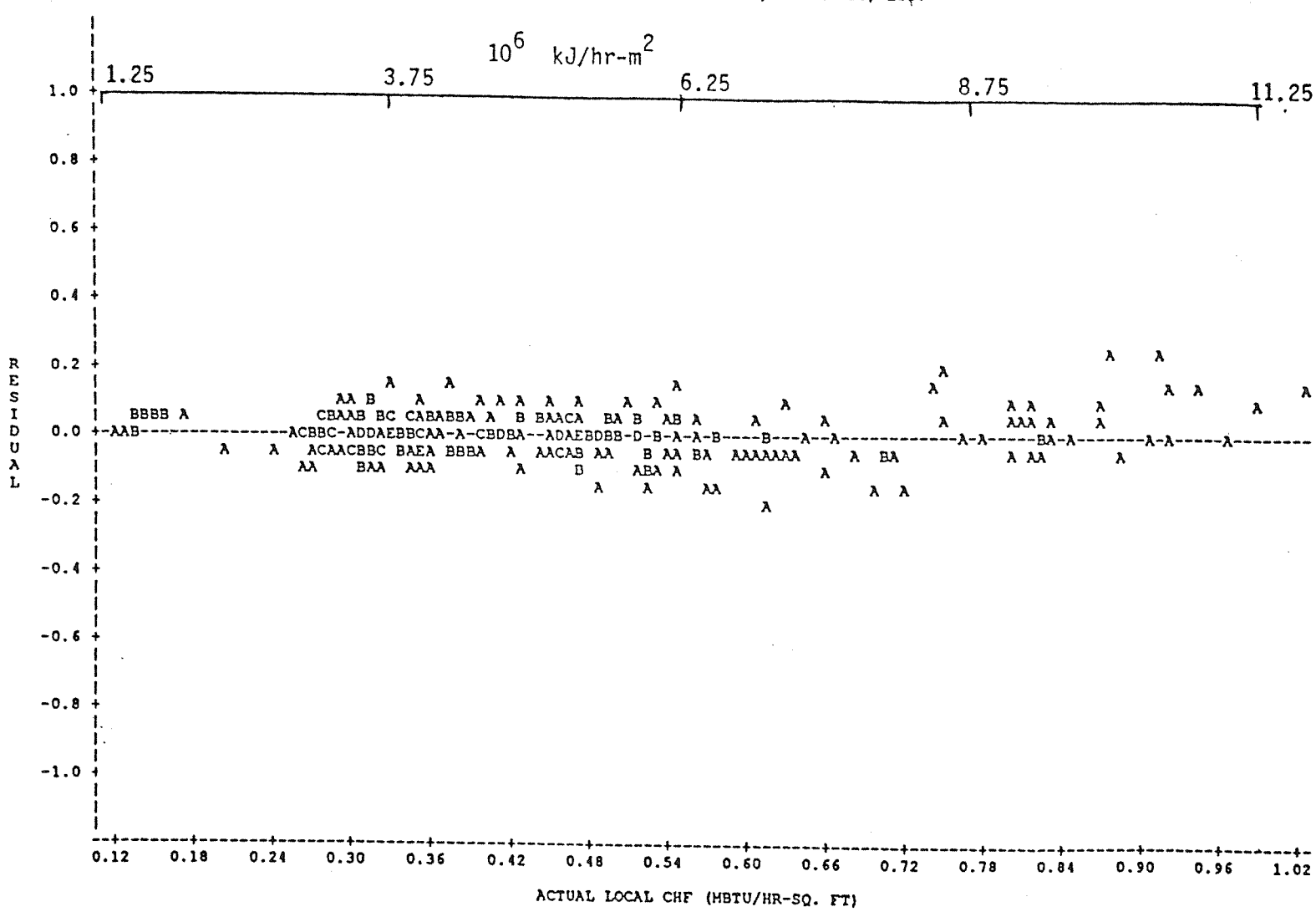

Figure 4. Scatter plot of Corr280 residual vs. actual local heat flux.

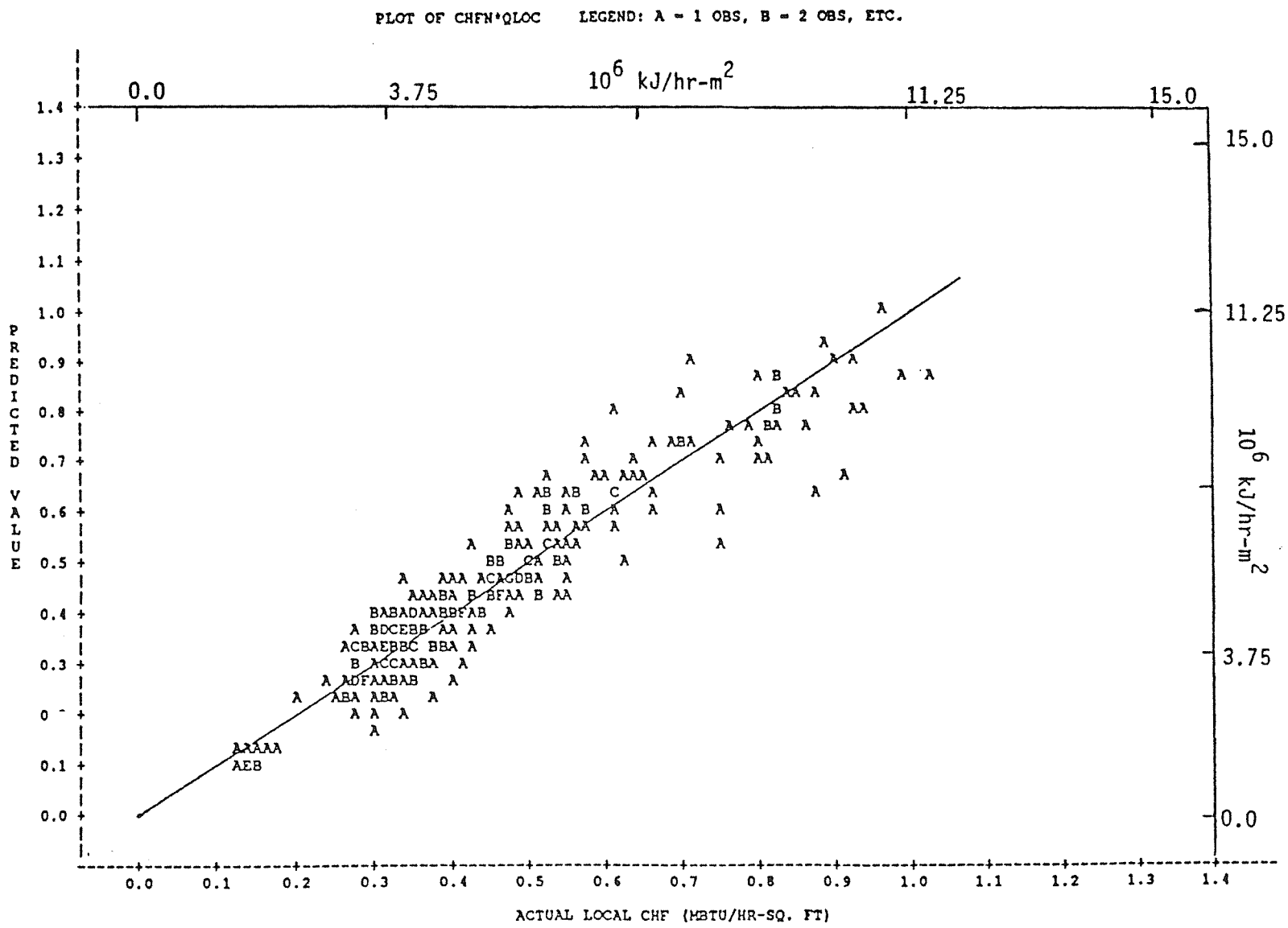

Figure 3. Predicted CHF vs. actual local heat flux for final result of Corr280.

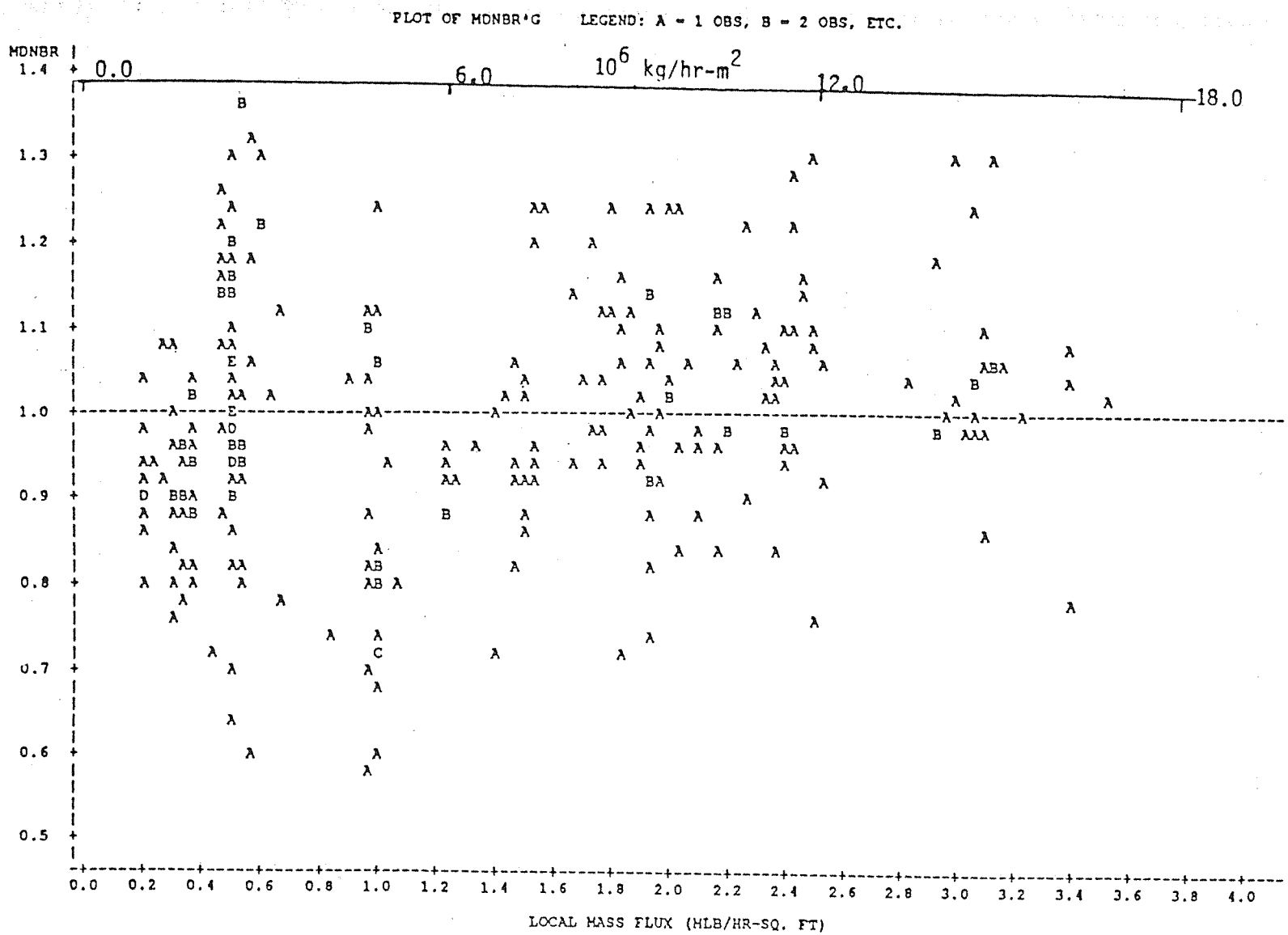

Figure 2. Minimum DNB ratio vs. local mass flux for final result of Corr280.

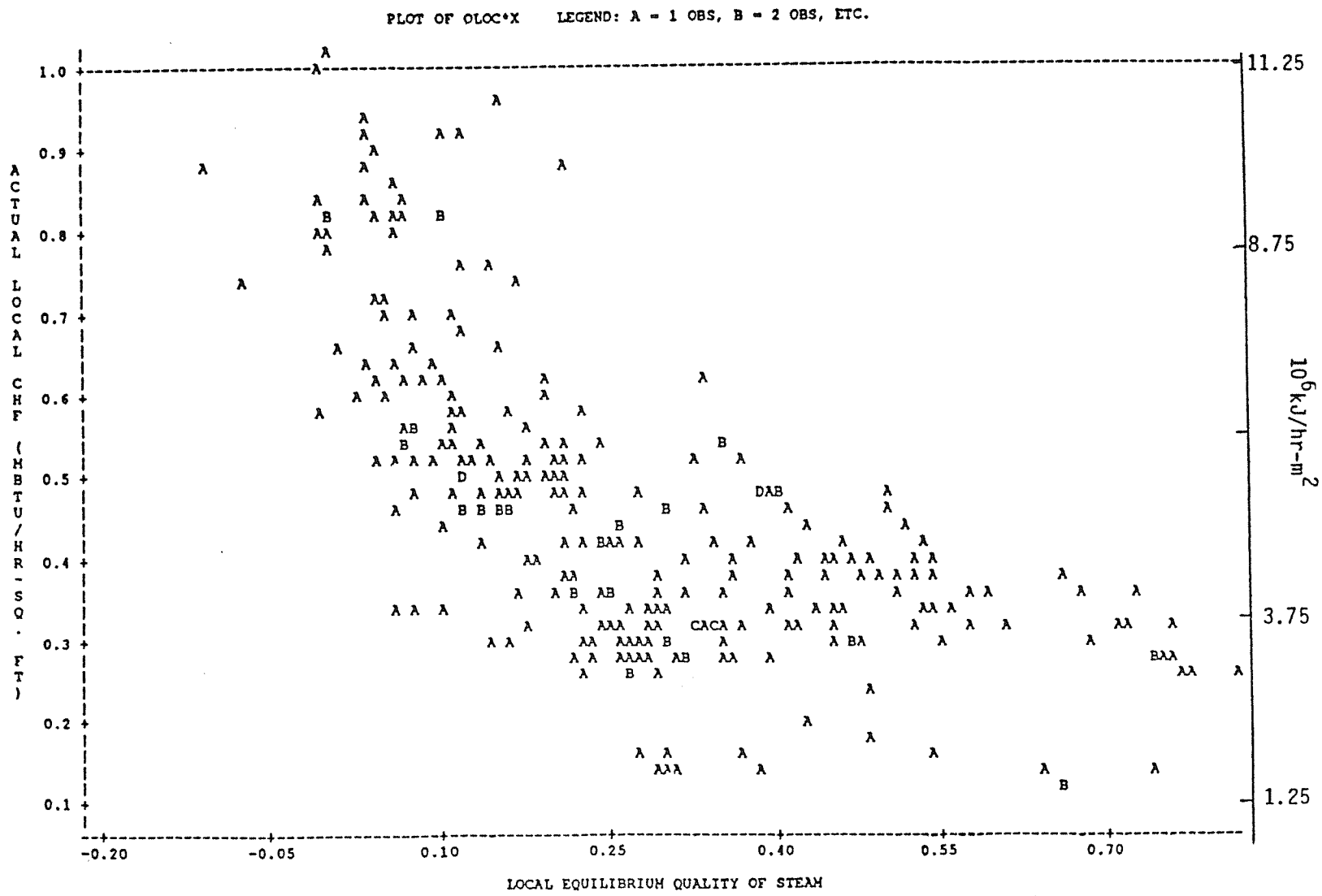

Figure 1. Actual local heat flux vs. local equilibrium quality of steam for final result of Corr280.

Table 2. Results of combinability, normality, and 95/95 design limit

Group	Size	Mean	Std. Dev.	F-stat	t-stat	Comb.?	Y	Normal?	Limit
All	278	0.994111	0.1451826	N/A	N/A	N/A	-0.81870	Yes	1.2563
Uniform flux	146	0.99441	0.151411				-1.61121	Yes	1.2780
				1.19442	0.03656	Yes			
Nonunif. flux	132	0.99378	0.138542				-0.34074	Yes	1.2551
0.374" pin (0.95 cm)	93	0.97450	0.170432				-0.01464	Yes	1.3048
0.422" pin (1.0719 cm)	88	0.99770	0.121354				-0.08846	Yes	1.2341
			(Bartlett)	(Gen. F)					
			12.71596	5.12803		No			
0.430" pin (1.0922 cm)	8	1.17900	0.107688				0.17223	Yes	1.5222
0.440" pin (1.1176 cm)	89	0.99444	0.130274				-1.57061	Yes	1.2480
No guide thimble	239	0.98250	0.148114				-0.91651	Yes	1.2519
			2.15091	4.40512		No			
Guide thimble	39	1.06530	0.100991				-0.15528	Yes	1.2807
72"(182.88 cm) leng. heated	8	1.17900	0.107688				0.17223	Yes	1.5222
84"(213.36 cm) leng. heated	89	0.99444	0.130274				-1.57061	Yes	1.2480
			(Bartlett)	(Gen. F)					
			3.08299	5.53170		No			
96"(243.84 cm) leng. heated	62	0.96336	0.141766				-2.28339	Yes	1.2490
168"(426.72 cm) leng. heated	119	0.99746	0.151393				-1.67662	Yes	1.2851
15" grid (38.1 cm)	8	1.17900	0.107688				0.17223	Yes	1.5222
16" grid (40.64 cm)	30	1.06227	0.172907				0.75345	Yes	1.4461
17.4" grid (44.196 cm)	59	0.95995	0.084920				-0.41389	Yes	1.1320
20" grid (50.8 cm)	31	0.90560	0.104420				0.84672	Yes	1.1362
			(Bartlett)	(Gen. F)					
			45.99593	10.32532		No			
22" grid (55.88 cm)	80	0.95859	0.172261				0.40763	Yes	1.2969
26" grid 66.04 cm)	55	1.04281	0.104937				-1.13838	Yes	1.2571
32" grid (81.28 cm)	15	1.08736	0.092505				-3.32419	No	1.2434
PREF<=1500 psia(10342.5 kPa)	213	1.00377	0.121720				-1.11194	Yes	1.2266
			2.75534	1.56453		No			
PREF>1500 psia(10342.5 kPa)	65	0.96245	0.202045				1.31230	No	1.3589
Local G<=1 Mlbs/hr-sq.ft(4.88x106 kg/hr-sq.m)	133	0.97726	0.154388				-0.74746	Yes	1.2683
			1.31011	-1.86142		Yes			
Local G>1 Mlbs/hr-sq.ft(4.88x106 kg/hr-sq.m)	145	1.00957	0.134884				-1.02707	Yes	1.2623

limit conservative thermal hydraulic design calculations can be performed. This design limit is good improvement in comparison with the value of 1.44 which is currently utilized by WCNOC.

Table 1. Optimized coefficients and range of data used.

number of samples = 278 variance = 0.0210780
mean of MDNBR = 0.994114 standard deviation = 0.1451826

[Optimized Coefficients:

P1= 0.599179317	P5= -1.667440027	a0= 0.139597114
P2= -0.620595508	P6= -2.555588434	a1= -0.0015039145
P3= 1.074352007	P7= 2.468766062	a2= -0.0018150213
P4= -0.199995256	P8= 3.620639729	b0= 1.0616028923
b1= 0.0001324029	b2= -0.9308366032	(Fgt= 1.0)

95/95 design limit of MDNBR = 1.36]

Rod bundle and fuel type:	PWR,R-type Westinghouse fuel (WH) , Combustion Engineering (CE) , Babcock & Wilcox (BW)
System pressure:	745.0 to 2415.0 psia (5136.8 to 16651.4 kPa)
Local mass flux:	
WH:	0.50948 to 3.53835 Mlbs/hr-sq.ft, If PREF<= 1500.0 psia (2.4863 to 17.2671 x106 kg/hr-sq.m) (10342.5 kPa)
	0.44387 to 1.01346 Mlbs/hr-sq.ft, If PREF> 1500.0 psia (2.1661 to 4.9457 x106 kg/hr-sq.m) (10342.5 kPa)
CE:	0.20086 to 0.52742 Mlbs/hr-sq.ft (0.9802 to 2.5738 x106 kg/hr-sq.m)
BW:	0.56179 to 0.65517 Mlbs/hr-sq.ft (2.7415 to 3.1972 x106 kg/hr-sq.m)
Local equilibrium quality:	-0.10976 to 0.77537
Local heat flux:	0.118824 to 1.029789 MBtu/hr-sq.ft (1.3494 to 11.6946 x106 kJ/hr-sq.m)
Inlet temperature:	244.4 to 590.0 oF (118.0 to 310.0 oC)
Heated length:	72.0 to 168.0 Inches (182.88 to 426.72 cm)
Mixing vane grid spacing:	15.0 to 32.0 Inches (38.1 to 81.28 cm)
Rod diameter:	0.374 to 0.440 Inches (0.95 to 1.1176 cm)
Number of rods:	16 (4X4) and 25 (5X5)

For nonuniform heat flux, the relationship in Eq. 19 is used with Tong factor defined in Eq. 20. A and C above are defined in Eq. 18. Table 1 shows the optimized coefficients and the range of parameters for this correlation. The linear relationship of local CHF with local quality of steam can be seen in Figure l. As quality increases the local CHF decreases. At high quality of steam the graph looses its linearity. This is where the temperature difference keeps getting smaller but the CHF decreases at a smaller rate than before. This part of the gragh is where Qloc and X are not linearly related anymore.

7.2. Scatter plots for Biasing and Accuracy

It is necessary to verify that the correlation describes the CHF phenomenon for the data set accurately, without bias toward any variables in the model. The best way of checking for bias is by producing scatter plots of the predicted correlation MDNBR against independent variables. Any bias with respect to these variables will then show as a trend toward deviation from the horizontal. Figure 2 is the scatter plot of local mass flux. Figure 3 is the plot of the predicted CHF against the actual local CHF at the MDNBR location. It shows the correlation ability to predict Chf is uniform over the range of MDNBR's predicted.

7.3. Results of Dependency and Collinearity

In order to check for the dependency of the correlations, it is necessary to produce the scatter plots of the residual against dependent and independent variables. Figure 4 shows the scatter plot of the residual vs. dependent variable. Almost all the data for all of these figures lie between −0.17 to 0.17 of the residual which is an indication of good results. There is no dependency in the models (no deviation from the horizontal).

For collinearity , the partial correlation coefficient between the independent variables are checked (for final ouput data). If the correlation coefficient is close to 1.0, it is concluded that there is a collinearity problem betwen the independent bariables. The following results obtained;

independent variables (R2)	correlation coefficient
GSP & ZCHF	0.33009535
GSP & X	0.29469860
ZCHF & X	0.02158034

It should be noted that the correlation coefficients are much smaller than 1.0, and it is concluded that there is no collinearity problen among independent variables.

7.4 combinability and Normality Tests

The values listed in Table 2 for y of d Agostino s D−test are for normality tests. This is two sided test at 0.05 level of significance. It was found that all the sample groups are from normal population except the 32 "(81.28cm) grid spacing group and the range group for pressure greater than 1500 psia (10342.5 kPa).

7.5. Statistical Limit Determination

for the entire population of 278 points, the limit is calculated to be 1.2563. Similar calculation resulted in the other limit values listed in table 2. The nonparmetic 32" (81.28 cm) grid spacing subgroup and the range subgroup for pressure greater than 1500 psia (10342.5 kpa) were each placed in acsending order of MDNBR. The 95/95 limit for these groups are 1.2434 and 1.3589, respectively. Therefore, it was concluded that the design limit of 1.36 is safe for WCNOC design of low pressure or low flow CHF.

8. CONCLUSIONS

Visual examination of scatter plots and the numerical evaluation of statistical performance indicate that the correlation is applicable to WH R−type fuels with mixing vane grids and/or CE and BW tests of similar geometry with WH bundles, within the operating envelop it was designed for. The correlation show no bias toward local fluid properties.

In determining the overall 95/95 design limit of the correlation it is necessary to consider how the subgroups are combined and what the statistics for the entire sample looked. The overall design limit is 1.2563. However, in order to be conservative, the recommended design limit is 1.36. By using this design

where the Tong factor is written as;

$$F_{TONG} = \frac{1}{b_0 Q_{loc}} \left[\frac{K}{1 - e^{-K(Z_{CHF} - Z_0)}} \right] \textit{(Integral)} \quad (20)$$

$$Integral = \int_{Z^0}^{Z_{CHF}} q''(Z)\, e^{-K(Z_{CHF} - Z_0)}\, dZ$$

$$K = \frac{0.15(1-x)^{4.31}}{G^{0.478}}$$

The only possible ambiguity in this equation is the definition of the boiling length . This term is the distance from the inlet to the location where boiling begins. In VIPRE-01 this distance is determined by selecting the location where the heat transfer regime changes from single- phase forced convection to subcooled nucleate boiling.

The method used to find the optimized values for coefficients of the base correlations is iterative, since the optimization process is carried out on predicted MDNBR'S rather than the test assembly CHF locations. The procedure is to first execute the VIPRE code to predict the local conditions at the location of MDNBR. The fluid conditions at these locations are then extracted and tabulated for input into the SAS nonlinear regression routine. The next step if necessary, is to force the mean of MDNBR for the database to be equal to 1.0 by adjusting the geometry correction factors and the non-uniform heat flux optimizing factor in FTong. This step is carried out by holding the coefficients optimized in the first step constant and determining the geometry correlation factors. The remaining factors have no dependence on the local fluid conditions so they are not part of the optimization process. These coefficients if necessary are adjusted using SAS so that the mean of the predicted MDNBR'S is 1.0. This is accomplished by setting up the statistical regression model to find the best fit set of the geometry coefficients that force the predicted CHF to equal the local heat flux at the MDNBR location. By best fit it is implied that each test run will not have the local heat flux at the MDNBR location equal to the predicted critical heat flux, but for the entire data set the average deviation from this condition will be minimized. when this step is done the correlations have their final forms. In order to have a reliable correlation it is necessary to check for dependency against dependent and independent variables and also check collinearity (two independent variables are highly correlated) among independent variables.

6. STATISTICAL METHODS FOR 95/95 DESIGN LIMIT

Chauvenet's test [14] was employed to eliminate points that can be considered outliers. Following the elimination process, tests were run on the data to determine the statistical design limit for each correlation. The first step was the calculation of the mean and standard deviation for the sample. Next, the D'Agostino's D test [15] was performed to see if each sample had a normal distribution. The data was then analyzed on a grouped basis to see if subsets of the data were similar enough to be considered combinable. The method used to calculate the 95/95 design limit (95% probability at the 95% confidence level) is the same method as prescribed in Reg. Guide 1.126 [16]. If the sample is from normal distribution, the method of owen [17] is used with the K factors corresponding to a one-sided 95/95 limit. If the sample is not normal, a nonparametric technique must be employed to obtain the 95/95 limit [18]. The method first requires that the sample be put in ascending order. Based on the sample size, the j the largest X value is chosen to be the 95/95 design limit.

7.RESULTS

7.1. Correlation Format and Optimized Coefficients

The final correlation form (with 278 data, two data were found to be outliers) for corr 280 is given as;

$$Q_{CHF,\,uni} = Fgeom\, [a_0 + a_1\,(GSP) + a_2\, z_{CHF} + (A-X)/C]$$

$$F_{geom} = [1 + b_1 + (GSP - 26.2)^2][1 + b_2\,(D_{pin} - 0.374)]$$

5. CORRELATION DEVELOPMENT PROCESS

The mass quality of a vapor – liquid mixture at a distance Z in a tube with uniform heat flux is given on a thermodynamic basis as,

$$X(Z) = \frac{H(Z) - H_f}{H_{fg}} \qquad (9)$$

and in terms of heat flux

$$X(z) = \left(\frac{1}{H_{fg}}\right)\left[\frac{4QZ}{DG} - \Delta H_{in}\right] \qquad (10)$$

Substituting the above equation into Eq.9 and after some manipulation for Q = QCHF.

$$QCHF = E + F\,\Delta Hin$$

where

$$E = \frac{DG}{4Z}\,[H(Z) - H_f] \qquad (11)$$

$$F = \frac{DG}{4Z}$$

Eliminating ΔHin between Eqs. 10 and 11

$$QCHF = M + NX(Z) \qquad (12)$$

where

$$M = \frac{E}{(1 - \frac{4Z}{DG}F)} \qquad N = \frac{-FH_{fg}}{(1 - \frac{4Z}{DG}F)}$$

Calculating E and F in Terms of M and N and then substitute into eq.

$$Q_{CHF} = \frac{A' + \frac{DG}{4}\Delta H_{in}}{C' + Z} \qquad (13)$$

where

$$A' = MC' \text{ and } C' = \frac{-DGH_{fg}}{4N}$$

Since DNB is a local phenomenon, it is important to obtain CHF in terms of local conditions. Bowring [13] has defined subchannel imbalance factor, Y′, which is the ratio of heat retained in the subchannel to the heat generated in the subchannel.

$$Y' = \frac{A_f G}{A_h Q_{loc}}\,(H_{ex} - H_{in})$$

After some substitutions and simplifications

$$(Z\,Y') = \frac{GD_h}{4}\left(\frac{X_{loc} - Xin}{Qloc}\right) H_{fg} \qquad (14)$$

For subchannel analysis, substitute (ZY′) into Eq. 13 instead of Z. Also using the following reltionships,

$$A = \frac{4A'}{GD_hH_{fg}} \qquad C = \frac{4C'}{GD_hH_{fg}}$$

Eq.13 after simplification becomes,

$$Q_{CHF} = \frac{A - X_{in}}{\left(C + \frac{X_{loc} - X_{in}}{Q_{loc}}\right)} \qquad (15)$$

By allowing QCHF = Qloc, the final form of Eq. 15 becomes,

$$Q_{CHF} = \frac{A - X_{loc}}{C} \qquad (16)$$

Eq. 16 can be also written as

$$QCHF = A1 - B\,Xloc \qquad (17)$$

Al and B are functions of the system pressure, local mass flux, enthalpy, etc. Eq.16 or 17 is the fundamental form of correlation used by many high margin venders today.

$$A = P_1\,(p_r{}^{P_2})\,(G^{(P_5 + P_7 P_r)}) \qquad (18)$$

$$C = P_3\,(p_r{}^{P_4})\,(G^{(P_6 + P_8 P_r)})$$

$$P_r = \textit{system pressure / critical pressure}$$

Where Pl to P8 are correlation coefficients that will take different values for different correlations and sets of data. The above equations are used for predicting CHF in a bundle with uniform heat flux. However, for nonuniform heat flux distributions, the modified tong factor is used as;

$$Q_{CHF,non} = \frac{Q_{CHF,uni}}{Tong\ Factor} \qquad (19)$$

b. The correlation is consistent with the VIPRE model that will be used for DNB analysis.

c. The correlation has been verified and accepted in the VIPRE safety evaluation report [SER, 11], or some other NRC document.

With these considerations in mind, the correlations used by the program were determined.

4.2. Turbulent Mixing Factor, ABETA

The turbulent mixing factor (thermal diffusion coefficient) is an empirical factor used to model the mixing between two adjacent channels due o turbulent cross flows. This cross flow affects the mixing of enthalpy and mass flux. Westinghouse has performed studies to determine applicable values of ABETA for different bundle array types and grid spacings. The results of these studies give the ABETA values that should be used in the VIPRE models of the columbia test data. These best estimate values for the mixing coefficient have been incorporated into the VIPRE models of the columbia test data. These best estimate values for the mixing coefficient have been incorporated into the VIPRE models used for the test section analysis. VIPRE is very sensitive to ABETA.

4.3. Channel Dependent Grid Loss Coefficients

The columbia test data as it is compiled in [7] gives average grid loss coefficients for the different types of grids used in the test assemblies. To provide a more accurate representation of the actual grid losses in the array of channels, a method is needed to convert the average value to channel specific values. The method selected is found on page 170 of reference [12].

The exact formulation for Rehme,s equation is given as:

$$\Delta p = C_v\,(S/A)^2\,G^2 / [2(rho)g_c] \qquad (5)$$

Assuming that the fluid properties are approximately the same for a subchannel as they are on an assembly average basis, and knowing that the Δp across the grid is constant whether individual channel or an assembly average loss ccoefficients are used, it is possible to find the channel dependent grid loss coefficients. In VIPRE, pressure drop due to grid spacers is calculated by:

$$\Delta P = C_d\,G^2 / [2(rho)\,g_c] \qquad (6)$$

The only difference between the above two formulations is the form of the loss term. To account for the grid frontal surface effect it is necessary to replace Cd by Cv $(S/A)^2$ in the VIPRE expression when calculating the pressure drop. In columbia report the average grid loss coefficient, CAA, is given. It is determined by experimental measurement of the pressure drop across the grid, the average mass flux, temperature, pressure of the system, and Eq.6 . Equating the loss terms of the assembly average value from EPRI with the assembly average from Rehme, we obtain ;

$$CAA = Cv\,[(S/A)^2]\ \text{assy}$$

or

$$Cv = CAA / [(S/A)^2]\ \text{assy} \qquad (7)$$

If the bundle subchannel loss coefficients are to be determined, Cd in Eq.6 is equated with Cv $[(S/A)^2]$ subchan where Cv is the same constant from the assembly average calculation. Therefore,

$$Cd = Cv\,[(S/A)^2]\ \text{subchan}$$

using Eq.7

$$Cd = CAA\,[(S/A)^2]\ \text{subchan} / [(S/A)^2]\ \text{assy} \qquad (8)$$

Eq. 8 is the formulation that must be used to caluculate the channel dependent grig loss coefficients from the assembly average values found in [7]. If this is done, the grid Δp determined from an experiment will be maintained in VIPRE model.The assumption made for this analysis is that (S/A)is proportional to (T/A) where T is the total area of the assembly or subchannel in question. This assumption is really based on another assumption, that the grid is uniformly distributed over the entire assembly. To insure that the assumption does not adversely affect the final solution, a study was done using the data for the fuel type currently in use at wolf creek. The results showed that the (T/A) method is valid as long as (T/A)is used in all plant models.

simplifying assumptions will be applied in consideration of the intended applications in VIPRE:

a. The flow is at sufficiently low speed.

b. work done by body forces and shear stresses in the energy equation are small compared to surface heat transfer and convective energy transport .

c. Heat conduction through the fluid surface is assumed small compared to convective energy transport and heat transfer from solid surfaces.

d. The phases are in thermodynamic equilibrium. (Tl=Tv=Tsat when voth phases are present).

e. Gravity is the only significant body force in the momentum equation ($\vec{F}=\vec{g}$)

f. Viscous shear stresses between fluid elements are assumed small compared to the drag force on the solid surfaces.

g. The fluid is incompressible but thermally expandable. (Density and transport properties vary only with the local temperature (enthalpy)).

Using all the assumptions described above and with some modifications and simplifications, the final form of the integral equations become Mass

$$\frac{\partial}{\partial t}\int_{\underline{V}} \pi d\underline{V} + \int_{\underline{F}} p(\vec{u}.\vec{n})d\underline{F} = 0 \qquad (2)$$

Energy

$$\frac{\partial}{\partial t}\int_{\underline{V}} phd\underline{V} + \int_{\underline{F}} ph(\vec{u}.\vec{n})d\underline{F} = -\int_{\underline{W}} (\vec{q}.\vec{n})d\underline{W} + \int_{\underline{V}} p.rd\underline{V} \qquad (3)$$

Momentum

$$\frac{\partial}{\partial t}\int_{\underline{V}} \vec{pu}d\underline{V} + \int_{\underline{F}} \vec{pu}(\vec{u}.\vec{n})d\underline{F} = \int_{\underline{V}} \vec{pg}d\underline{V} - \int_{\underline{F}} \vec{P}nd\underline{F} - \int_{\underline{W}} \vec{P}nd\underline{W} + \int_{\underline{W}} (\vec{\pi}.n)d\underline{W} \qquad (4)$$

The above three equations are used to develope subchannel equations. The actual local surface heat flux at each node for dummy rod geometry, where the rods are treated as simple heat sources or heat sinks, are calculated by using the experimental average heat flux of the whole core, in VIPRE code.First, the experimental values are converted to an average linear heat rate per rod. Then, the local surface heat flux is calculated as

$$q_{i,j} = LHR*F_iF_j \sum_{l=1}^{6} Q_{i,l}$$

More details are given in volume 2 and 5 of VIPRE manual.

3. DATA SELECTION METHODOLOGY

The dataset for the development of this correlation is a mixture of three different fuels. All the data are selected from critical heat flux (CHF) data published by the columbia University Heat Transfer Facility in EPRI report NP _ 2609 [7]. They all are tests done for PWR bundles. The criteria for selecting the appropriate data is based on references [8] and [9].

First set of data is from WH R-type fuel with mixing vane grids which has low pressure data (p<=1500psia (10342.5 kPa)) as the main criteria regardless of the mass flow rates; and also data with average mass fluxes of less than or equal to 1.0 Mlbs/hr – ft2 ($4.88x10^6$ kg/hr-m2)regardless of their pressures. The second and third sets of data are chosen from CE and BW test sections that have similar bundle geometries to WH tests. The criteria for choosing CE and BW data is to have an average mass flux of less than or equal to 0.750 Mlbs/hr-sq. ft ($3.66x10^6$ kg/hr-sq.m) regardless of their pressure. This set of data totals 280 points.

4. INPUT DECK MODELING DEVELOPMENT METHODOLOGY

Input decks are prepared using the instructions contained in the VIPRE-01 computer code Mathematical Modeling and User's Manual and references [8,10]. The process of preparing the decks is similar for all test cases. Specitic geometry and operating conditions must be entered, but most of the input remains the same for all the runs.

4.1. Correlation Selection

When determining the best correlations to use in the VIPRE models, the following criteria was used:

a. The correlation is applicable to the CHF subchannel analysis data range.

MDNBR Minimum Departure from Nucleate Boiling Ratio

WH Westinghouse

<<x>> Colume averaged quantity

<x> Surfaced averaged quantuty

1. INTRODUCTION

Boiling crisis in nuclear reactor fuel elements is characterized by a sudden drop in the heat transfer rate due to change of heat transfer mechanism and a temperature excursion of the fuel rod surface. The heat flux just before the occurance of boiling crisis is called critical heat flux (CHF) at which a small increase in heat flux or coolant inlet temperature to the reactor results in an ordinate deterioration of heat transfer and an attendant rise in the fuel rod surface temperature.

In general, there are two kinds of CHF data processing methods. One is the "subchannel method", in which the CHF data are reffered to the local parameters of the subchannel. In the other method the averaged parameters at the cross – section are used.

It is often the case that some rods reach the condition of DNB mainly due to local parameters and are independent from the averaged parameters over the total cross section of the cluster [1]. But the averaged parameters are easier to measure and do not require large computer codes either to develop or to use CHF correlations. However, These correlations are valid only for conditions representative of the data on which they are based [2]. They can not be used with high degree of confidence to predict CHF in a new rod bundle with different geometry or with different radial or axial heat flux profiles. Noailly [3] reports that the subchannel analysis code predicting the local variables in pressure, mass velocity, and quality plus the DNB correlation constitute an overall tool to determine the DBN physical limits. A better knowledge of the DNB limits allows for the increase of core performances in power and temperature. It is therefore of primary importance that the same subchannel analysis code used for design purposes be used to reduce the DNB experimental data. The Bernath correlations [4,5] because of its generality, has been used extensively for CHF analysis. However, Wadkins, et al. [6] reports that Bernath correlation is unacceptable for a tightly packed, low pressure, rod prediction. Wadkins and his co–workers performed CHF tests at low pressure in a closed packed rod bundle. They concluded that closed–packed rod bundles operating at low pressure have low CHF values, conditions in the gap have a dominant effect on CHF, and CHF initiates in these gaps. They also concluded that rod bowing further reduced CHF in the condition tested.

The objective of the present investigation is to develop a correlation for low pressure and/or low flow rate CHF for Wolf creek Nuclear Operating Corporation (WCNOC), using the computer code VIPRE (Versatile Internals and Component Program for Reactors; EPRI). A design limit for the correlation will also be obtained.

2. SUBCHANNEL FLUID FLOW ANALYSIS IN VIPRE

The integral balances are performed on an arbitrary Eulerian control volume, V, that is bounded by a fixed surface, $\underline{A}$. Any volume – averaged mixture quantity, Q, (Units/ unit Volume) can be expressed as the volume – weighted sum of the individual vapore and liquid phase quantities as

$$Q = \alpha Q_v + (1-\alpha)Q_l$$

The integral balance for the arbitrary mixture property, Q, is written as

$$\frac{\partial}{\partial t}\int_{\underline{V}} Q d\underline{V} + \int_{\underline{F}} Q(\vec{u}.\vec{n})dF = \int_{\underline{V}} s_v \, d\underline{V} - \int_{\underline{F}} (\vec{s}_A.\vec{n})d\underline{F}$$

(storage) (convection) (volume source) (fluid surface source)

$$- \int_{\underline{W}} (\vec{s}_A.\vec{n})d\underline{W}$$

(wall surface source)(1)

Conservation equations of mass , energy, and momentum are derived by letting Q becomes the mass, energy, or momentum per unit volume. The following

F_{geom} Total correlation factor for geometry
F_{gt} Grid thimble tubes factor
F_i Radial powerfactor for rod i
F_j Axial power factor for rod i at node j
F_{Tong} Tong factor
F Fluid surface of Eulerian control volume
f Axial friction factor (Darcy), f=4f′
f′ Axial friction factor (Fanning)
G Mass flux (velocity)
GSP Grid spacing
g Gravity vector
H Enthalpy or average enthalpy of liquid layer
ΔH_{in} Enthalpy subcooling at channel inlet
h Flowing enthalpy
K_G Lateral form loss coefficient
K′ Equivalent loss coefficient per unit width
LHR Average linear heat rate
l Adjacent channel centroid distance
m Axial mass flow rate
n Unit outward normal vector
p Pressure
P_r Ratio of system pressure over critical pressure
P_w Rod perimeter πd
Q Arbitrary volume intensive quantity
Q Heat flux
Q_{loc} Local heat flux
q Heat flux vector
q′ Linear heat rate
q″ Heat flux
rho Fluid density
r Internal heat generation per unit mass
S Gap width
S Grid frontal surface area
S_V Volumetric source term
S_A Surface source term
T temperature
T Total area of assembly or subchannel
U Axial Velocity
$\vec{U}$ Vector velocity
U′ Axial momentum transport velocity
$\underline{V}$ Eulerian control volume
v Specific volume
v′ Specific volume for momentum
$\underline{w}$ Wall surface of Eulerian control volume
w Crossflow per unit length
w′ Turbulent crossflow
x Flowing or local quality
x_{loc} Local quality
Z Channel length
Z_{CHF} Distance from the beginning of the heated length where CHF is predicted
Z_{sc} Length of tube under subcooled condition
Z_o Boiling length

Greek Letters

α Void fraction
θ Orientation angle measured from vertical (degrees)
ρ Density
ϕ Two - phase friction multiplier
ϕ_{in} Fraction of rod n's heated perimeter connected to channel i
Ψ Tong's function relating flowing and static quality
$\vec{\vec{\pi}}$ Viscous stress tensor

Subscripts

assy Assembly
ex Exit
f Saturated liquid or liquid
fg Difference between saturated vapor and liquid
ii, jj Index of adjacent channels where jj is larger than ii in Inlet
l Liquid
non Non – uniform
sat Saturation
subchan subchannel
v Vapor
uni Uniform

Special Notion

BW Babcock and Wilcox
CE Combustion Engineering
Corrx Correlation with database of X points
DNB Peparture from Nucleate Boiling
EPRI Electric power Research Institute

Nuclear PWR Development of a CHF Correlation Design Limit at Time of Accident

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ABSTRACT

A correlation has been developed for low pressure and/or low flow critical heat flux (CHF)in pressurized water reactors (PWR)based on subchannel analysis of local fluid conditions. The correlation is applicable to wolf Creek Nuclear Operating corporation (WCNOC) fuel and rod assemblies. The correlation uses 280 data points from three different fuel types. Data is chosen such that it has either pressures less than or equal to 1500 psia (10342.5 kpa) or mass fluxes less than or equal to 1.0 Mlbs/hr - sq. ft ($4.88x10^6$ kg/hr - sq.m). The correlation has been developed based on the equation that describes CHF as linearly dependent on quality of steam. Optimization of the correlation coefficients and the development process are done using the computer code VIPRE (versatile Internals and component program for Reactors; EPRI) and SAS nonlinear regression method.

NOMENCLATURE

A	Axial flow area or channel unrestricted flow area
A_f	Flow area
A_h	Heat transfer area
A	Surface of an Eulerian control volume
C_{AA}	Average grid loss coefficient
C_d	Grid loss coefficient defined in VIPRE
C_Q	Fraction of power generated directly in the coolant
C_T	Turbulent momentum factor
C_V	Grid loss coefficient
D	Diameter
D_h	Hydraulio diameter based on wetted perimeter $4A/p_w$
D_{pin}	Fuel pin outside diameter
e_{ik}	Crossflow direction switch function