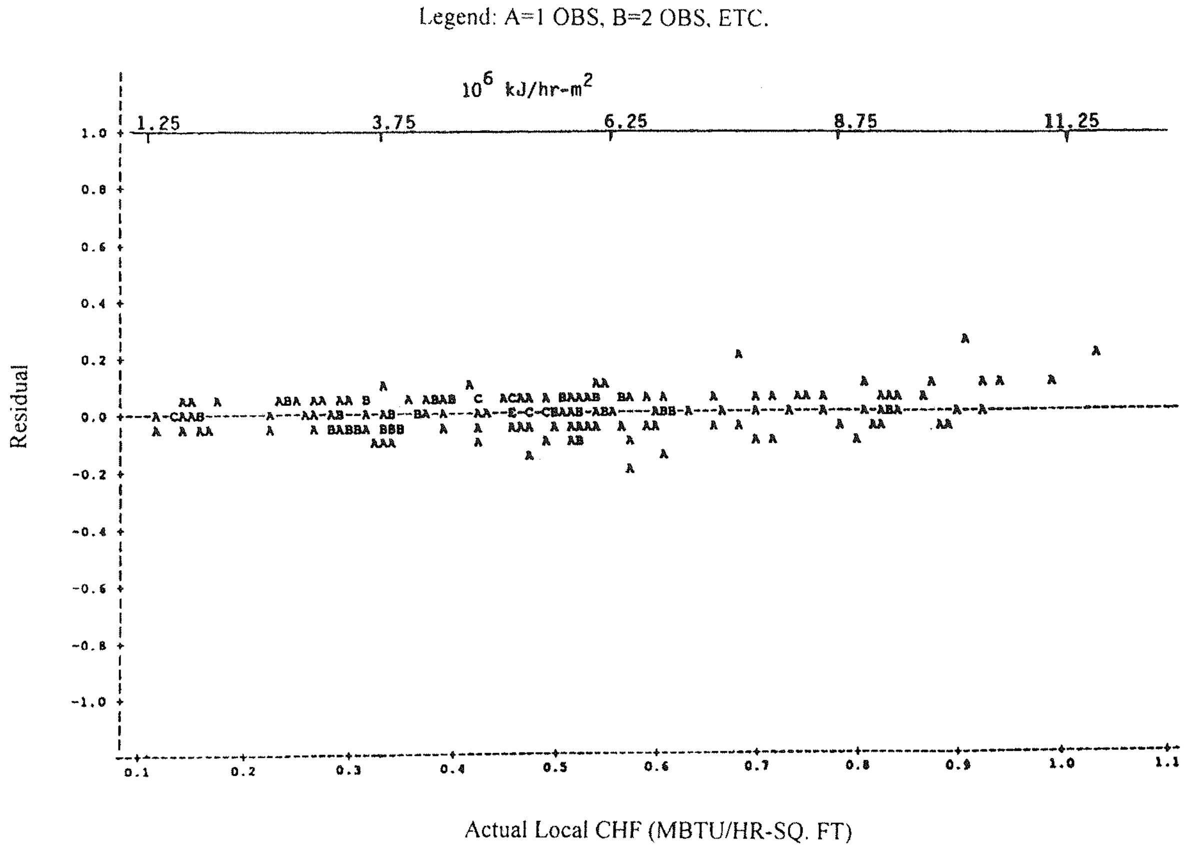

Figure (4) Scatter plot of Corr183 residual vs. actual local heat flux..

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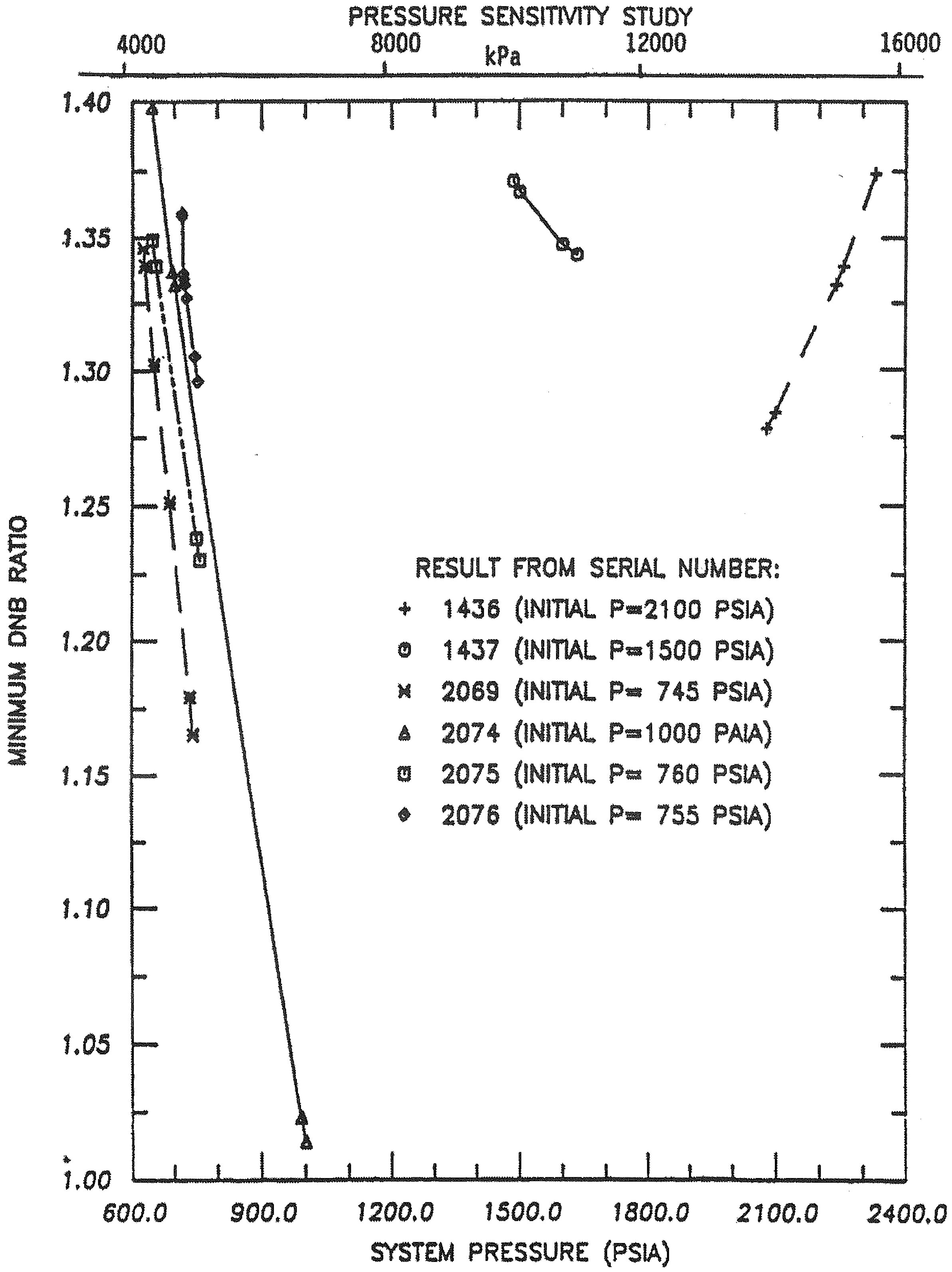

Figure (5) MDNBR vs. system pressure for six different cases of Corr183, design limit 1.34.

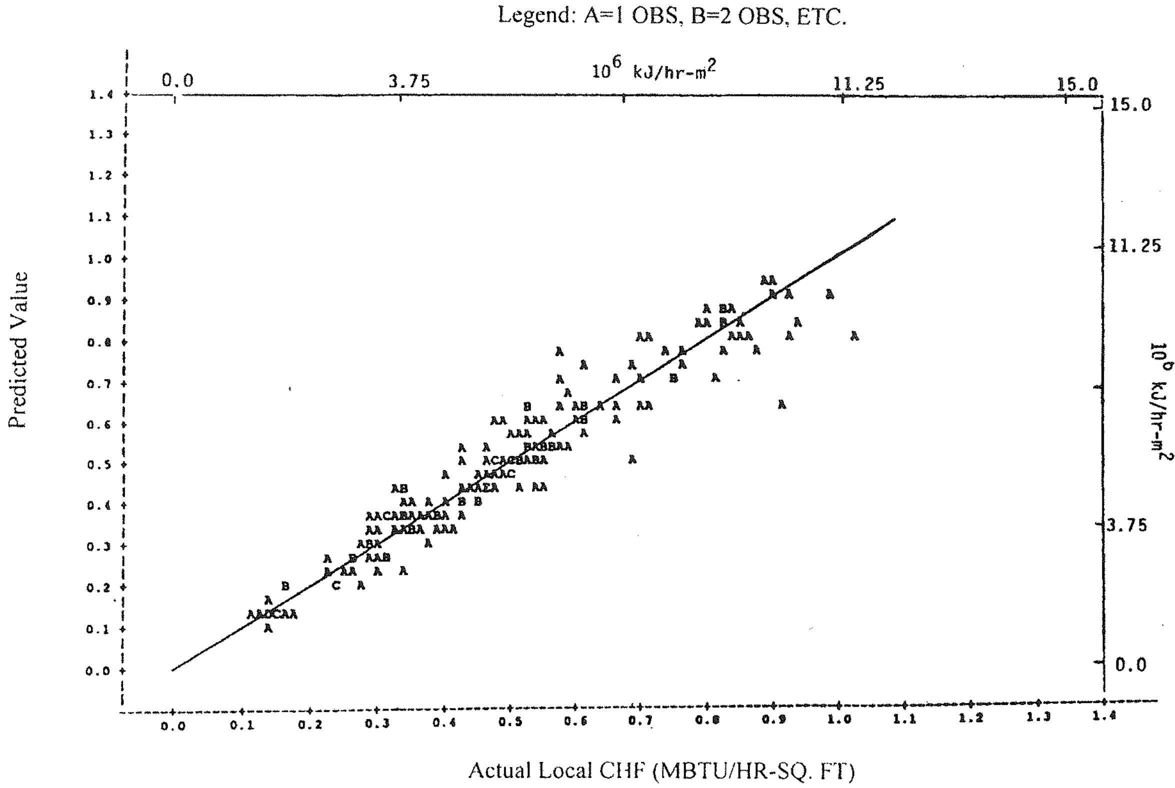

Figure (2) Predicted CHF VS. actual local heat flux for final result of Corr183.

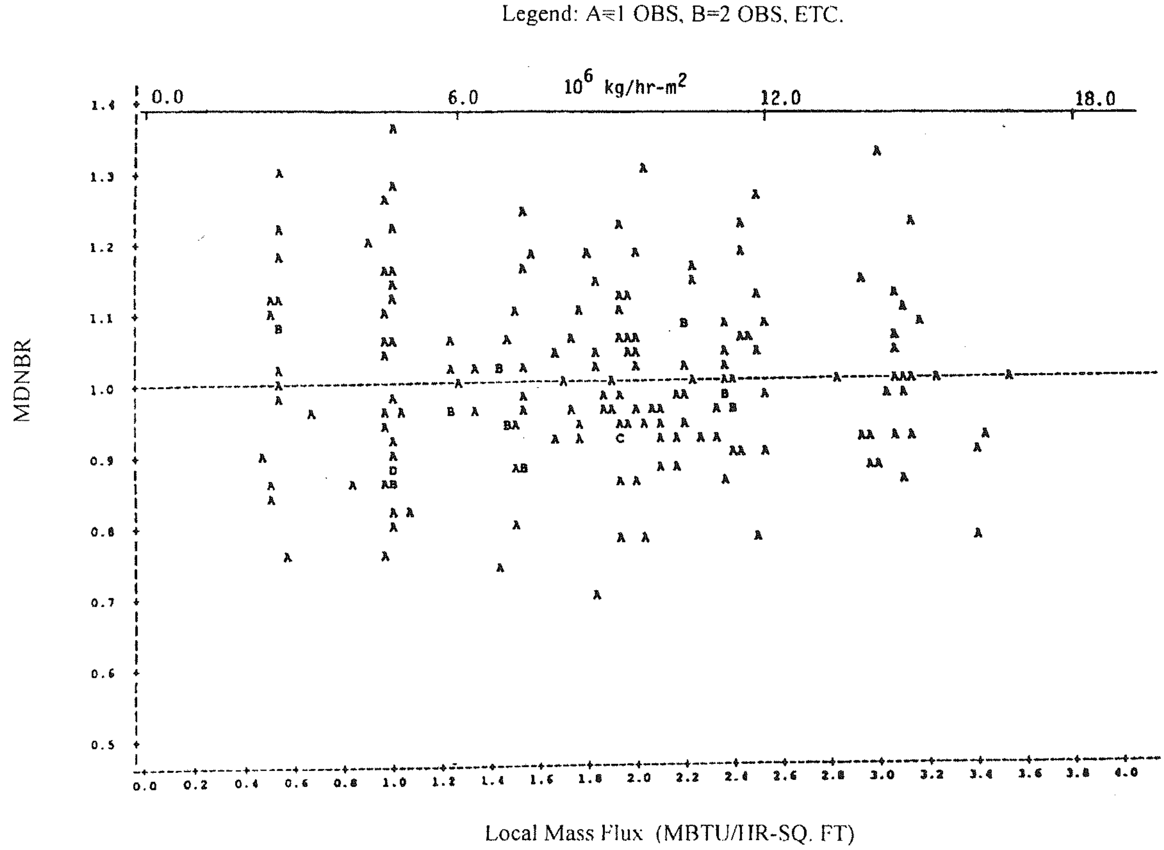

Figure (3) Minimum DNB ratio VS. local mass flux for final result of Corr183.

comparison with the value of 1.44 which has been utilized by WCNOC till late 1990's.

The methodology is logical and clearly registered. Many parts of the technique are also used by many venders and/or are approved by ANSI. 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 look. Consideration of all the flow and geometrical properties in CHF correlation development and its design limit are well suggested. In CHF correlation development the base equation to start with is to consider the heat flux as to be linearly dependent to local equilibrium quality. The final form of correlation is achieved when it is tried to force the predicted CHF to be equal to local CHF at the MDNBR location (mean of MDNBR be equal to one).

Nomenclature

ANSI	American National Standards Institute
CHF	Critical Heat Flux
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio
D_{pin}	Fuel pin outside diameter
di	Deviation from observation i
F_{geom}	Total correlation factor for geometry
F_{gt}	Grid thimble tubes factor
F_{tong}	Tong factor
G	Mass flux
GSP	Grid Spacing
k	Number of subgroups
MDNBR	Minimum DNBR
m	sample mean
N	Total number of samples in all subgroups
n	Number of samples (observations)
p	Pressure
$Q_{CHF/non}$	Non-uniform CHF
$Q_{CHF/uni}$	Uniform CHF
s	Standard deviation
T	Multiple of standard deviation
WCNOC	Wolf Creek Nuclear Operating Corporation
X	Flowing or local quality
X_{loc}	Local equilibrium quality
Z	Channel Length
Z_{CHF}	Distance from the beginning of the heated length where CHF is predicted

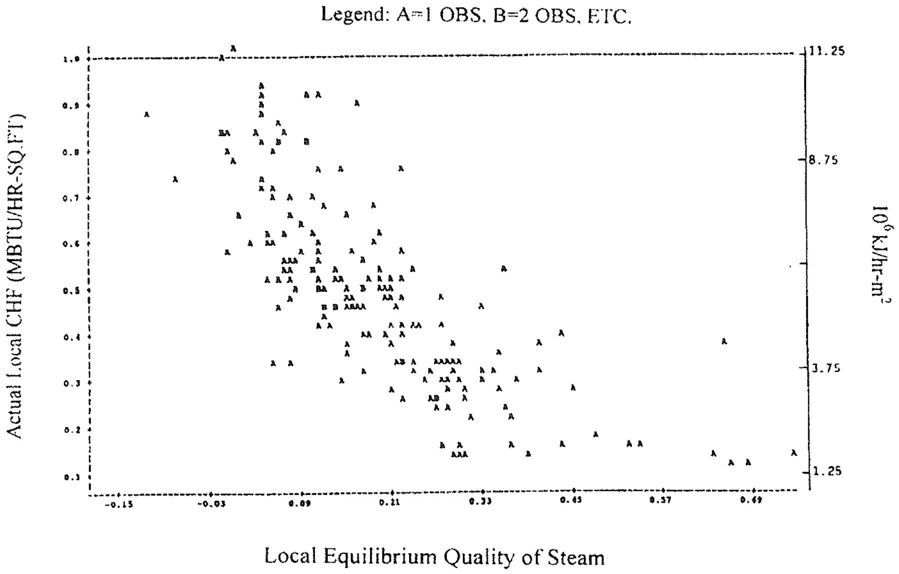

Figure (1) Actual local heat flux vs. local equilibrium quality of steam for final result of corr183.

95/95 design limit.

The final recommended 95/95 design limit is that of a subgroup which is not combinable and which has the highest 95/95 design limit value, unless the recommended design limit is specified otherwise. One specification is that the number of samples in a subgroup be close to true representation of the whole dataset. At the last it is recommended to perform studies in order to verify that the correlation with its new design limit is sensitive to operating conditions (pressure, mass flux,...) and observe its thermal-hydraulic margins. It should be noted that sensitivity analysis is more an informational rather than safety related study.

4-Results and Conclusions

The above method has been successfully used in [2] for development of three different correlations design limit which apply to WCNOC. Linear relationship of local CHF with local quality of steam (approval of Eq.1) can be seen in Figure 1. As quality increases the local CHF decreases. At high quality of steam the graph looses its linearity. For the points in the subcooled region where CHF happens at low quality, which is close to the inlet of the bundle, the temperature difference between the rod and coolant is high and so is the CHF. The reverse is true when the quality of steam is high (saturated region). In saturated region as the temperature of coolant gets higher the quality of steam also increases. This will continue up to a point were the layer of steam would act as insulator between the coolant and the rod wall. This is where the temperature difference keeps getting smaller but the CHF decreases at a smaller rate than before. This part of the graph is where Qloc and X are not linearly related anymore.

Study of effect of local fluid conditions are shown in figures 2 and 3. Figure 2 is an example of the plot of the predicted CHF against the actual local CHF at the MDNBR location. Visual examination of this plot shows no bias in the correlation with respect to any of the variables especially the local fluid conditions. It also shows that the precision of the correlation is uniform over the ranges of all the variables tested which indeed shows the accuracy of the methodology used for development of correlation. This figure indicates the correlation ability to predict CHF is uniform over the range of MDNBR's predicted. Figure 3 is an example of plot of MDNBR versus local mass flux. Similar plots of MDNBR versus local equilibrium quality and system pressure could be obtained. The absence of bias in last two graphs indicates that the correlation accurately describes CHF with respect to local fluid conditions.

Figure 4 shows the scatter plot of the residual versus dependent variable, actual local CHF. For independent variables similar plots could be obtained. Almost all the data lie between -0.18 to 0.18 of the residual which is an indication of no dependency in the model (no deviation from the horizontal).Figure 5 which is an attempt of sensitivity study shows the effect of starting pressure on operating conditions. Slope of each line increases as the starting pressure increases. The slope angle for each case depends on its physical input data. This sensitivity study shows good margins. By this method described in this paper the maximum design limit which has been obtained in different studies for low pressure and/or low flow CHF is 1.36. This design limit is a great improvement in

It is also important to check for collinearity (two independent variables are highly correlated) among independent variables. In that case one of the variables should be eliminated from the model.

3-Statistical Methods for 95/95 Design Limit

To qualify the correlation which has been developed for safety related thermal-hydraulic calculations, a justifiable 95/95 DNBR design limit (95% probability at the 95% confidence level) must be determined and reasonable statistical performance must be shown. The statistical tests that are suggested are selected because they are either the best tests available for the particular requirement, or they are recommended choice by the American National Standards Institute for this type of application.

a) **F-Test** [5] is used to check the equality of variance between two sets of data when the population could be divided into two subgroups (like using two different rod diameters). This is a two sided test and the values should be checked at the 0.05 level of significance (95%probability), so it is necessary to check the critical values of F in proper tables at 0.025 and 0.975 probability with n-1 degrees of freedom for each subgroup. The calculated value of F must fall between the upper and lower bounds in order to conclude that the variances are equal.

b) Along with the F-Test, the **Student T-Test** [5] is used to check the equality of means between two subgroups of data. This test like the F-Test is a two sided test so the same conditions apply.

C) To say that the two subgroups under consideration are combinable requires that F-Test and Student T-Test both pass.

d) **Bartlett's Chi-Square Test** [5] is used for equality of variance among several sets of data when the population could be divided into more than two subgroups (like using four different rod heated length). This is a one sided test so the look up value in proper tables is at 0.95 with k-1 degrees of freedom. If the calculated value is less that the critical value, the variances are concluded to be equal at the 0.05 level of significance.

e) Along with the Bartlett's Test, the **General F-Test** [6] for equality of means of several subgroups is used. This is a one sided test so the same conditions as Bartlett's Test apply with degrees of freedom equal to k-1 and N-k.

f) To say that the subgroups under considerations are combinable, requires that the Bartlett's Chi-Square Test and General F-Test both pass.

g) **D'Agostion's D-Test** [7,8] for normality of a sample is used. This is a two sided test so the same conditions as the F-Test apply.

h) **Performance of 95/95 design limit** could be done as follows. If the sample is from normal distribution, the method of Owen [9] is used with the K factors (in proper tables) corresponding to a one sided 95/95 limit.

$$95/95 \text{ Design Limit} = m + sK \qquad (6)$$

If the sample is not normal, a nonparametric tolerance limits technique [10] is employed to obtain the 95/95 limit. This method first requires that the sample be put in ascending order. Based on the sample size the x largest value in proper tables will be the revising of the correlations in place and local fluid conditions at MDNBR locations are extracted from the computer code. The correlation is then reoptimized as described earlier. The new coefficients are again put into the correlation and the computer program is updated. These procedures are carried out until the local conditions at the predicted MDNBR remain approximately the same for two consecutive iterations. At this point it is concluded that the correlations are optimized for CHF predictions based on local fluid conditions.

During these procedures it is important to attempt to eliminate any points appear to be **outliers.** Such points will have extreme MDNBR values that will have a large effect on the mean, standard deviation, and normality of sample. One method, Chauvenet's Criterion [4], has been shown to be an effective technique for this purpose. For the sample size of n data points a rule of thumb is to base the rejection rule on 1/2n for probability deviation. If the probability is smaller than 1/2n, it is very unlikely that such a large deviation should occure even once in a set of n data points. This method is expected that about one percent of the data will be eliminated. The upper and lower bounds for MDNBR to be used as rejection values can be formulated as (T=di/s);

$$\begin{aligned} \text{Upper bound} &= m+Ts \\ \text{Lower bound} &= m-Ts \end{aligned} \qquad (5)$$

T and di/s are read from proper tables. After elimination of outliers the optimization process is continued with the rest of data.

The next step is to force the mean of MDNBR for the database to be equal to 1.0 by adjusting the geometry correlation factors in F_{geom} and the non-uniform heat flux optimizationn factor in F_{Tong}. This step is carried out by holding the coefficients optimized in the first step constant and delermining 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 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 geometry coefficients that forces 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 CHF, but for the entire dataset the average deviation from this condition will be minimzed. Since MDNBR is just the ratio of the CHF divided by the actual heat flux at MDNBR location, this ratio will be equal to 1.0 when the geometry coefficients are optimized. When this step is done the correlation have its final from. Fig. 2. (studied in [2]) is showing the final state of this step.

Dependency and Collinearity Check

In order to have a reliable correlation it is necessary to check for dependency against dependent and independent variables at which the biased scatter plots of residual model vs. the dependant and independant variables in the model must be removed. Also scatter plots of the predicted correlation MDNBR against independent variables must be produced. Any bias with respect to these variables will then show as a trend toward deviation from the horizontal. Figs. 3. and 4. are examples of scatter plots of MDNBR versus local mass flux and residual versus actual local CHF studied in [2] which show unbiased results.

developed). This computer code should either be tested for similar different cases of the proposed study or to be licensed by ANSI. After modeling the data based on subchannel analysis and feeding that into the computer code, the best correlations for different part of calculations are determined. The empirical calculations used in the model must have ranges of application that encompass the anticipated operating conditions the model will be used to simulate. When this is not apparent, logical assumptions will be made based on physical data as to which correlations can be used.

Some of the important correlations which need to be determined before developing the CHF correlation are two-phase flow correlation, heat transfer correlation, friction factor correlation, turbulent mixing factor that has significant effect on final results, and channel depenent grid loss coefficients which is also important to final results. The above mentioned correlations must be chosen based on the range of data and kind of reactor analysis used by researcher. The mechanism for choosing these correlations are beyond the scope of this paper.

2-Chf Correlation Development Process

This section describes the methodology which is used to develop the CHF correlation. The predicted CHF should be as close to the local heat flux as possible. Usually, the basic correlation form to start with is similar to

$$Q_{CHF,uni}=A-BX_{loc} \qquad (1)$$

which is used by many high margin venders today. Heat flux is linearly dependent on local equilibrium quality and A and B are functions of the system pressure, local mass flux, enthalpy, etc. From the above equation in most cases

$$Q_{CHF,uni}=f\left(F_{geom}, GSP, Z_{CHF}, X, P, G\right) \qquad (2)$$

is obtained where,

$$F_{geom}=f\left(F_{gt}, GSP, D_{pin}\right) \qquad (3)$$

Different coefficients in the CHF correlation are optimized to produce a mean MDNBR for the CHF database equal to 1.0. For non-uniform heat flux distributions a factor like Tong Factor [1,2] is used such that,

$$Q_{CHF,non}=\frac{Q_{CHF,uni}}{\text{Tong Factor}} \qquad (4)$$

Linear dependency of heat flux to local quality of steam could be seen in Fig. 1. which is studied in [2] about 181 dataset points. The technique required to optimize the correlation is a non-linear regression procedure like SAS[3].

By running the computer code the fluid properties at local conditions of the CHF locations should be extracted in order to develop a base correlation like Eq.2. The first step is to optimize the coefficients for the terms found in Eq. 2. with the exception of F_{geom} (Eq. 4. must be used to include the non-uniform CHF_s). This method is iterative. The procedure is to first execute computer code to predict the local conditions at the location of MDNBR. The fluid conditions at these conditions are then extracted and tabulated for input into the statistical nonlinear regrssion routine in order to obtain the optimized coefficients for this set of local condition data. The new coefficients are put into the correlations and the computer program is updated. The test cases are run with the first

An Applied and Safe Procedure at Nuclear Water Reactors for Development of Critical Heat Flux Correlation and its Design Limit

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Abstract

In order to justify the operating limits at actual nuclear plants, development of a design limit is a necessity. This paper describes the techniques involved in development of critical heat flux correlation (regression model) and its design limit for safety purposes of nuclear water reactors. The procedure involves all conservative statistical modelings. The method uses the basic relationship between critical heat flux and local equilibrium quality which are linearly dependent on each other. The technique that is required to optimize the correlation is a non-linear regression process. Detection of outliers, collinearity check, and biasing toward a variable are considered. Checks for equality of standard variations, means, normality, and design limit of subgroups of samples and /or whole correlation data are also considered.

1-Introduction

From the point view of reactor safety, the accidental loss of coolant is the most important danger ever reported. This involves a very complicated thermodynamic and hydrodynamic phenomenon. Nucleate boiling is the preferred mode of heat transfer for operation. The operating criteria for nuclear reactors specify that they must operate under conditions below critical heat flux (CHF) in order to maintain the cladding temperature of fuel elements at safe values. CHF is one of the most important parameters which limits the maximum power at which nuclear reactors can operate. Therefore, it is very important to be able to predict the value of CHF in order to prevent departure from nucleate boiling (DNB) from the safety and economy of a nuclear reactor. Improvements of methods for the prediction of CHF is a subject of vital importance in nuclear reactor design and has been extensively studied during the last 40 years. Current understanding of the CHF phenomenon is not good enough for the theoretical expressions to be used for predictions. Instead, empirical correlations of experimental results are used. The objective of the present investigation is to develop a methodology for obtaining a CHF correlation and its design limit for nuclear reactor operations. It should be noted that this is not the only method which exists. However, it has approved to be a logical, safe, acceptable, and conservative technique.

The process will begin with selection of the experimental database of CHF data which is based on its similarity to the core and fuel type used for specified purposes. A flexible computer code for thermal hydraulic analysis of nuclear reactors, which is suggested to be based on subchannel method, is chosen (or