WESTINGHOUSE CLASS 3

WCAP-8763-A

NEW WESTINGHOUSE CORRELATION *WRB-1* FOR PREDICTING CRITICAL HEAT FLUX IN ROD BUNDLES WITH MIXING VANE GRIDS

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Work Performed Under DGRF 03200 and DGRF 40206

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

APR 19 1978

Mr. C. Eicheldinger, Manager
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Pittsburgh, Pennsylvania 15230

Dear Mr. Eicheldinger:

SUBJECT: STAFF EVALUATION OF WCAP-7956, WCAP-8054, WCAP-8567, AND WCAP-8762

The Nuclear Regulatory Commission staff has completed its review of the following Westinghouse Electric Corporation topical reports.

WCAP-7956 (Non-proprietary), "THINC-IV, An Improved Program for Thermal-Hydraulic Analysis of Rod Bundle Cores" June 1973

WCAP-8054 (Proprietary) and WCAP-8195 (Non-proprietary), "Application of the THINC-IV Program to PWR Design," September 1973

WCAP-8567 (Proprietary) and WCAP-8568 (Non-proprietary), "Improved Thermal Design Procedure," July 1975

WCAP-8762 (Proprietary) and WCAP-8763 (Non-proprietary), "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids," July 1976.

Our evaluations of these reports are enclosed.

As a result of our review of WCAP-7956 and WCAP-8054, we have concluded that the THINC-IV computer code is acceptable for performing steady-state hydraulic calculations in reactor cores provided suitably conservative assumptions are used with respect to plant operating conditions, fuel fabrication tolerances, and power peaking uncertainties. Fluid conditions are limited to the single phase or the homogeneous two phase flow regime. Limitations on the use of the THINC-IV code are provided and fully discussed in our evaluation of these topical reports (Enclosure 1).

WCAP-8567 describes a new procedure for calculating departure-from-nucleate-boiling ratio (DNBR) in reactor cores based on the statistical combination of uncertainties in plant parameters that affect DNBR.

As a result of our review, of WCAP-8567, we have concluded that the new thermal design procedure is acceptable for use in licensing applications subject to the imposition of certain restrictions and changes to the procedure. The sensitivity factors for plant parameters are valid only for the W-3 DNB correlation, THINC-IV computer code, and the range of plant parameters considered in the report. Sensitivity factors, variances, and distributions for plant parameters must be included and justified in each plant safety analysis report. Code uncertainties specified by the staff (+4% for THINC-IV and +1% for transient analyses) must be included in DNBR analyses. Fuel rod bowing effects cannot be treated as described in the report; however, addition of a rod-bow penalty to the DNBR limit is acceptable. A plant transient resulting from a loss of reactor coolant flow must satisfy the design basis DNBR limit for faults of moderate frequency (ANS Condition II event) rather than the design basis limit for infrequent accidents (ANS Condition III event) as specified in WCAP-8567. The improved thermal design procedure is applicable only to DNBR analyses and cannot be used in other analyses, such as overpressure calculations. The acceptable conditions for use of the improved thermal design procedure are fully described in our safety evaluation of WCAP-8567 (Enclosure 2).

As a result of our review of WCAP-8762, we have concluded that the WRB-1 critical heat flux correlation is acceptable for use in thermal-hydraulic calculations of pressurized water reactor cores provided a DNBR limit of 1.37 is used for cores composed of fuel assemblies with an "L" grid design. The proposed DNBR limit of 1.17 is acceptable for cores composed of fuel assemblies with an "R" grid design. The limit of 1.37 for "L" grid designs results from a large variation in data for the limited number of tests run with this design. This limit may be reduced by obtaining additional test data or by additional analytical work to improve the correlation. Our evaluation, including an independent audit of calculations to determine local coolant conditions for the tests and an independent audit of the statistical calculations used to establish the DNBR limit, is summarized in Enclosure 3.

Accordingly, topical reports WCAP-7956, WCAP-8054, WCAP-8567, and WCAP-8762 are acceptable for reference in license applications. Topical reports WCAP-8195, WCAP-8568, and WCAP-8763 are acceptable non-proprietary versions of the proprietary reports. When these reports are used as references, both the proprietary report and the non-proprietary version must be referenced.

In accordance with established procedure, it is requested that Westinghouse issue revised versions of these reports within three months of receipt of this letter to include the NRC acceptance letter, the enclosed evaluations, and any changes resulting from the review.

We do not intend to repeat our review of these reports when they appear as references in a particular license application except to assure that the material presented in these reports is applicable to the specific plant involved.

Should Nuclear Regulatory Commission criteria or regulations change, such that our conclusions concerning these reports are invalidated, you will be notified and given an opportunity to revise and resubmit your topical reports.

Sincerely,

John F. Stolz, Chief
Light Water Reactors Branch No. 1
Division of Project Management

Enclosures:
1. Topical Report Evaluation
   WCAP-7956 and WCAP-8054
2. Topical Report Evaluation
   WCAP-8567
3. Safety Evaluation Report
   WCAP-8762

cc: D. Rawlins
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ENCLOSURE 3

ANALYSIS BRANCH

DIVISION OF SYSTEMS SAFETY

OFFICE OF NUCLEAR REACTOR REGULATION

WCAP-8762

SAFETY EVALUATION REPORT

ON

WRB-1 CRITICAL HEAT FLUX CORRELATION

MARCH 1978

WRB-1 SER

Introduction

The staff has reviewed the WRB-1 Critical Heat Flux (CHF) correlation as presented in topical report WCAP-8762. The staff evaluation of the WRB-1 CHF correlation is presented in this report.

The Westinghouse Rod Bundle, critical heat flux correlation (WRB-1) is an empirical correlation which specifies the critical heat flux (i.e., the heat flux at which departure from nucleate boiling occurs) as a function of local conditions in a rod bundle. The local conditions in the rod bundle were calculated with the standard Westinghouse thermal hydraulic design code THINC. This correlation is based on 24 test series with a total of 1147 data points. Each of the 24 test series was conducted on an electrically heated rod bundle containing from 9 to 25 rods. Each test series corresponds to a different rod bundle geometry except for one repeatability test series. The 24 test series include variations in heated length, rod size and configuratic spacer grid design, grid spacing, and axial heat flux distribution.

The range of coolant condition tested corresponds to the proposed range of coolant conditions for application to PWRs.

Westinghouse has indicated that the WRB-1 correlation may be used to replace the W-3 correlation in the core thermal hydraulic design for both the 15x15 fuel assembly design and the 17x17 fuel assembly design. The Westinghouse topical report WCAP-8762 concludes that the WRB-1 correlation is significantly more accurate than the W-3 correlation in predicting departure from nucleate boiling. On the basis of the improved correlation accuracy the proposed value of a minimum departure from nucleate boiling ratio (DNBR) to meet the reac design criterion of a 95% probability of not experiencing departure from nucleate boiling on a limiting rod at a 95% confidence level is 1.17. The comparable value for the W-3 correlation is approximately 1.3.

Scope of Review

The staff review of WCAP-8762 has included an independent audit of the subchannel calculation performed to determine the local coolant conditions in the rod bundle. Approximately 300 calculations have been performed with COBRA-IV and the results have been compared with the published results from the Westinghouse THINC calculations. The staff review has also included an independent audit of the statistical calculations used in establishing the DNBR design limit for the correlation. The staff has reviewed the assumptions made in generating the CHF correlation and the DNBR design limit as well as the assumptions necessary in order to apply the correlation to the PWR geometry and coolant conditions. The WRB-1 correlation was also compared to other PWR CHF correlations to identify any anamalous behavior. During the review, the staff requested and received additional information in several areas.

Review Summary

Results of Audit Calculations

The results of the staff audit calculations are presented in Tables I, II and III. Table 1 presents a comparison of calculated local quality for THINC and COBRA-III and IV. Both the THINC code and the COBRA code have been reviewed and compared to experimental data; and we concluded that either code could be used to establish the local conditions required for the development of the CHF correlation. The comparison indicates a very good agreement between the two methods. Since the THINC and the COBRA-III and IV calculations are both subchannel calculations the term "local conditions" refers to average conditions in a subchannel. Each subchannel in the rod bundle is represented in both codes and the effects of flow redistribution are included. Table II presents the results of a typical COBRA-IV calculation for one of the CHF tests. These calculations indicate that the enthalpy distribution in the test bundle is nearly uniform. It appears that the rod powers and the peripheral channel hydraulic diameters were chosen, in most cases, to produce a nearly equal enthalpy rise in each channel. This minimizes the effects of crossflow and interchannel mixing since fluid exchange between adjacent channels does not result in any significant energy exchange. The analysis of the local coolant conditions is therefore relatively insensitive to changes in thermal d fusion coefficient, spacer grid flow resistance, crossflow resistance and other modeling assumptions. This is a sound approach to CHF testing since it minimizes the possible effects of calculational bias and calculational uncertainties on the resulting CHF correlation.

During the initial phase of the staff review of this correlation only COBRA-III was available. Subsequently COBRA-IV became available allowing comparisons among the three subchannel codes.

Table III presents a comparison of the Measured CHF/Predicted CHF for THINC and COBRA-IV. The mean values of the Measured CHF/Predicted CHF and the standard deviations are in good agreement. Table IV presents a similar comparison between COBRA-III and COBRA-IV for test series A-1 (throughout this report the test series will be designated by the identification given in Table 3-1 of WCAP-8762). A standard, statistical analysis of variance test, the F-test, was performed on the THINC, COBRA-IV results for tests series A-1. The purpose of this test was to determine if differences in the method of calculating the local coolant condition were responsible for the observed variation in the CHF data. The results of this F-test clearly indicate (i.e., at a 99% certainty) that the variation among the mean values of Measured CHF/Predicted CHF predicted by THINC, COBRA-III and COBRA-IV is much smaller than would be expected from a random sample with the same variation among the individual data points. This implies that it is unlikely that the variation among the data points is the result of the method of solving for the subchannel coolant condition.

The good agreement between THINC and COBRA-III and IV in terms of local conditions and Measured CHF/Predicted CHF; and the relatively simple nature of the subchannel calculations indicate that the uncertainty in the local subchannel condition has only a small contribution to the overall uncertaint in the correlation. The difference between the COBRA-III and COBRA-IV individual cases was generally less than 1%; and the difference between the COBRA-III and COBRA-IV values for the mean of the Measured CHF/Predicted CHF was less than 0.1%. The differences between the THINC and COBRA-IV individual cases were generally on the order of 2% or less; and the differences between the THINC and COBRA-IV values for the mean of the Measured CHF/Predicted CHF were generally less than 1%. However, in the cas of test series A-5 a consistent bias of greater than 1% found between the THINC results and the COBRA results. This difference was traced to the cosine axial power distribution used by Westinghouse which was not fully normalized (i.e., average axial power = 1.008 rather than 1.00). This difference results in a conservative bias in the Westinghouse results for the A-5 test series. In addition, it should be noted that many of the test series which form the basis for the WRB-1 correlation were also used to support previous Westinghouse DNBR correlations, and that many of these test series were previously subjected to review and comparisons to COBRA calculations.

Correlation Assumptions

The assumed form of the correlation and the modeling of average subchannel coolant conditions rather than actual local coolant conditions are important considerations in determining the acceptability of the correlation. Additional assumptions related to the application of the correlation to PWRs will be discussed later. The form of the WRB-1 correlation is as follows:

$$q\ CHF = PF + A1 + B3 \times Flow = B4 \times Flow \times Quality$$

where:

PF (Performance Factor) is a function of mixing vane design

A1 is a function of Pressure, Flow, Heated Length to the CHF location, Grid Spacing and Distance from the last grid

B3 is a constant

B4 is a function of Pressure, Flow and Heated Length.

Correlations using a similar form have been used successfully in the past and the general trend of decreasing CHF with increasing fluid quality has been observed in many experiments. The correlation also depends on Pressure, local flow, heated length, grid spacing, distance from the last grid, hydraulic diamete and mixing vane design. The form of the correlation relative to these parameter and the correlation coefficients are highly empirical. In some instances the physical basis for the individual correlation terms is not apparent. The inclusion of a term for the heated length appears to result in a more accurate correlation but the physical basis for this term is unclear. In a correlation which uses actual local conditions, a heated length term would appear to be unnecessary. Another example of an apparently non-physical representation in the WRB-1 correlation is the separation of the mixing vane design effect from the grid spacing effect. The mixing vane grids have the effect of promoting downstream turbulent mixing and an upstream flow reduction due to the flow resistance. It is reasonable to expect that the effect on CHF would be a function of the grid spacing. A large grid spacing, for example, could result in the downstream turbulent mixing effect washing out before the next mixing vane grid could reestablish the turbulent mixing pattern. Previously published Westinghouse data (WCAP-7411-1-P-A) on various mixing vane designs and grid spacing appear to show a dependence of the mixing vane design effect and on the grid spacing.

These are two examples of areas in which the correlation may not be correctly representing the physical phenomena. This has two important implications; first, a non-physical representation of phenomena in the correlation could be a contributing factor to the scatter in the comparison of Measured CHF and Predicted CHF for a given series of tests. This effect is inherently accounted for in the statistical analysis of the data for that given test series. The second implication of having non-physical representation of important phenomena is that the extrapolation of the WRB-1 correlation to other geometries of coolant conditions may not be valid. In fact the practice of combining data from different geometries in calculating an overall correlation uncertainty may not be valid. This subject will be discussed more extensively in a later section of this report.

An important new feature of the WRB-1 CHF correlation is the inclusion of a term which accounts for the distance (DG) between the CHF location and the last upstream mixing vane grid. This term reflects the observed behavior in which CHF occurred predominantly in locations just upstream of a mixing vane grid. WCAP-8762 indicates that the WRB-1 correlation, including the DG term, has an overall 81.7% accuracy in predicting the location of CHF. The method of establishing this accuracy is discussed on page 3-6 of WCAP-8762. It appears that this accuracy in predicting the correct location of CHF is a major factor in reducing the scatter of the data within each test series. Since there is a physical basis to expect the CHF to depend on the distance from the last mixing vane grid and since it appears to make the correlation more accurate the use of the DG term is acceptable. In response to a staff question, Westinghouse stated that in the THINC subchannel analysis of the CHF data, the axial node just below a mixing vane grid was assumed to have a value of DG equal to the full grid spacing. This treatment is acceptable but requires that the same assumption be made in the application of the WRB-1 correlation to PWR calculations.

The WRB-1 CHF correlation uses average subchannel coolant conditions as input. This technique inherently excludes consideration of the flow distribution, temperature distribution or void distribution (i.e., flow pattern) within a subchannel. Since the mixing vane grids and unheated rods can affect the distribution of flow, temperature and voids in the subchannel, the correlation needs empirical terms to account for these effects. The use of a subchannel analysis in developing the correlation implies that a similar technique needs to be used in the application of the correlation. Since there are important phenomena on a scale smaller than a subchannel, the use of a subchannel analysis means that the correlation must include empirical terms. As discussed previously, the empirical nature of the correlation may be one of the important contributing factors to the overall correlation uncertainty and has important implications relative to extrapolation of the correlation. The staff positions relative to the extrapolation of the correlation and the establishment of the DNBR limit will be discussed in a later section of this report.

Statistical Review

The WRB-1 correlation has been reviewed to determine if there are any residual trends (i.e., systematic variations in the Measured CHF/Predicted CHF) as a function of coolant conditions. When the data from the 24 test series are viewed as a whole, there do not appear to be any residual trends with changes in coolant conditions. Figures 3-4, 3-5 and 3-6 in the topical were presented to demonstrate the lack of such trends. The data have also been reviewed to determine if there are any systematic trends with changes in geometry. This can be tested by comparing the variance in the data from one test series with the variance in the data from a second test series. When looking for systematic variations among three or more test series the variation in the test series means can be compared to the variation of the data within the test series. In both cases a standard statistical analysis of variance test can be applied to determine if the differences found are statistically significant. In fact, the presence of systematic variations can be identified with any degree of confidence desired. The analysis of variance, F-test, has been used to identify systematic variations among the test-series at a 99% confidence level. The results of these tests are summarized in Table-V, which presents the calculated values of F and the theoretical range of F values at a 99% confidence level for truly random data. Where:

$$F = S_B^2/S_W^2$$

S_B^2 = variance of the means of the test series

S_W^2 = variance of the data within the test series

The theoretical range given in Table V shows that if the data were truly random there is a 99% probability that the calculated value of F would fall within that range. A value of F below the range indicates that there is too little variation among the means and a value of F above the range indicates that there is too much variation among the means. Sixteen individual F-tests were performed to determine if systematic trends exist among the test series. As indicated in Table-V only three of the 16 F-tests results in values within the expected range. For truly random errors all 16 would have been expected to fall within the range. In a few instances the F-value is below the expected range. This appears to be the case for those test series which were used in establishing the form of the correlation or the correlation coefficients. In other words the correlation was chosen to minimize the variations in the Measured CHF/Predicted CHF. In these cases the correlation was chosen in a manner which eliminated some of the natural variations between the test series. For most of the comparisons given in Table-V, the calculated value of F significantly exceeded the maximum expected value. The implication of these systematic trends is that the change in geometry from one test series to another introduces another component of variance. The following example is presented to illustrate the potential problems associated with combining all of the test series results to establish a DNBR limit without accounting for a component of variance due to geometry changes. As indicated in Table 3-1 of WCAP-8762 the mean value of the Measured CHF/Predicted CHF for all 1147 data points is 1.0043 and the corresponding stanc deviation is 0.0873. This mean value and this standard deviation were used to establish the proposed DNBR limit of 1.17; where the intent is that a calculatec value of DNBR of 1.17 corresponds to 95% probability (at a 95% confidence level of not experiencing DNB. In dealing with the CHF data the DNBR corresponds to the Predicted CHF/Measured CHF. Therefore the DNBR limit corresponds to a Measured CHF/Predicted CHF value of 1/1.17 or 0.855. The expected percentage of data points with a Measured CHF/Predicted CHF below 0.855 would therefore be approximately 5%. Test series A-20 includes 36 data points. We would therefore expect that fewer than two data points would have values of Measured CHF/Predicted CHF less than 0.855. The actual data indicate that six data points were below 0.855, which is more than three times the number which the correlation implies. Similarly, the mean value of 1.0043 for all 1147 data points implies ~50% of the data have values above 1.0043 and ~50% have values below 1.0043. For test series A-20 none of the data points has a value of Measured CHF/Predicted CHF above 1.0043, in fact none has a value above .9402. Clearly, the mean value and standard deviation of all 1147 data points have little or no meaning when we are dealing with the test geometry for series A-20. Similar problems, generally of smaller magnitude, exist when the mean value and standard deviations based on all 1147 data points are compared to other of the test series. Combining all the data together in this manner, in establishing a DNBR limit, is only valid if there are no systematic trends among the results from the various test series.

The WRB-1 correlation appears to predict the CHF test data reasonably well; and the mean value and standard deviations of Measured CHF/Predicted CHF for each individual test series (presented in Table 3-1 of WCAP-8762) appear to be valid indications of the correlation accuracy relative to that test series. None of the 24 test series used a geometry which is exactly the same as one of the Westinghouse fuel assembly designs. Some of the test series are very close to the fuel assembly designs while these include geometry variations (8 foot and 14 foot heated lengths for example) which bound the actual values used in the fuel designs. The test series most representative of the Westinghouse 17x17, 14-foot fuel design are: A-1, A-2, A-5, A-18, the test series most representative of the 17x17, 12-foot fuel design are: A-1, A-2, A-3, A-4, A-5, A-18, A-19; the test series most representative of the Westinghouse 15x15, R grid, 12-foot fuel design are A-6, A-7, A-8, A-9, A-10. A-11, A-12, A-13, A-14, A-15, A-16, A-17; the test series most representative of the Westinghouse 14x14 L grid and 15x15 L grid, 12-foot fuel design are: A-20, A-21, A-22, A-23, A-24. An analysis of variance was performed to determine if there is any significant components of variance among these four groups of test series. The results of this analysis indicate that the R-grid data can be treated as a single data set where the variance of the data is represented by two components, one component to account for variance within a given test series and a second component to account for the observed variance among the test series. Similarly, the L-grid data can be treated as a single data set with its own values of variance within the test series and variance among the test series. For both groupings of data, the total variance can be calculated as follows:

$$\sigma_{Total}^2 = \sigma_W^2 + \sigma_A^2$$

where:

σ_W^2 = variance within the test series about the mean value

σ_A^2 = variance among the test series means.

The combined degrees of freedom for these two groupings (i.e., R-grid and L-grid) have been calculated on the basis of a weighted harmonic mean of the degrees of freedom for the data within the test series and for the data among the test series. The following formula was used:

$$F_T = (\sigma_W^2 + \sigma_A^2)^2 \; / \; (\sigma_W^4/f_W + \sigma_A^4/f_A)$$

where:

F_T = combined degrees of freedom

σ_W^2 = variance within the test series about the mean

σ_A^2 = variance among the test series means

f_W = degrees of freedom for the data within the test-series

f_A = degrees of freedom for data among the test series means.

Table VI summarizes the results of these calculations. The differences in σ_W and σ_A shown in Table VI for the R-grid and the L-grid data demonstrate that a single value of σ_W or σ_A for all the data would not be appropriate.

The cause of the increased variation among the L-grid test series means relative to the R-grid test series means is not fully known. One possible explanation is that the heated length effect is different for L-grids than for R-grids and that the heated length effect in the WRB-1 correlation is not appropriate for L-grid designs. This speculation is supported by the fact that, for the L-grid tests, the three lowest test series mean values of Measured CHF/Predicted CHF were all associated with the eight foot tests and the three highest test series mean values of Measured CHF/Predicted CHF were associated with the 14-foot tests. This can be seen by comparing the test series means on Figure 2. In addition, direct comparisons can be made between test series which are geometrically identical except for the grid design. There are four cases in which these direct comparisons can be made. For the two 8-foot comparisons, (i.e., test series A-21 vs. A-9 and A-21 vs. A-14) the L-Grid means were lower than the R-grid means (1.59% and 2.77% respectively). For the two 14-foot comparisons, (i.e., A-22 vs. A-7 and new data from tests W-206 to 216 vs. A-6) the L-grid means were higher than the R-grid means (5.58% and 4.47% respectively). These comparisons also indicate that the length effect may be different for L-grid tests and R-grid tests. If there is a real difference in the length effect of L-grids, then the length effect in the WRB-1 correlation is conservative since it produces a higher DNBR limit.

Assumptions for PWR Application

Having reviewed the WRB-1 correlation relative to the CHF data, what remains to be determined is the applicability to PWR design. Three areas have been reviewed relative to PWR application of the WRB-1: first, limitations of the correlation related to geometry and coolant conditions; second, uncertainties introduced by CHF test atypicalities; and third, establishment of an appropriate DNBR correlation limit.

The proposed range of coolant conditions is based on the range of all the data.

Based on the empirical nature of the correlation, the range of application should be based on the range of the data. In terms of geometry, the correlation should not be applied to any PWR geometry which has not been specifically tested or which has not been bracketed by the test data. The important parameters to which this applies are: rod size, rod pitch, heated length, mixing vane design and grid spacing.

The following differences between the CHF test and the Westinghouse PWR fuel designs have been reviewed: the inclusion of simple support grids between the mixing vane grids in the CHF test but not in the actual fuel design; heated length; number of rods, grid spacing, and use of stainless steel rods.

The use of stainless steel rods is an industry standard which is not believed to introduce a significant uncertainty relative to PWR applications. Although the heated length and grid spacing in the CHF tests is not the same as is used in Westinghouse PWR designs the values tested were sufficiently close to the design values; and the CHF tests also included ranges of heated length and grid spacing which cover the range of design values. The question of the use of simple spacer grids is more complex than the other atypicalities. In the CHF tests the rods are electrically heated and the magnetic forces resulting from the electric current could cause the rods to bow in a manner which is not typical of PWR conditions. In order to reduce or eliminate this potential rod bowing, the CHF tests include simple support grids to prevent rod motion. These simple support grids were designed to minimize their effect on the local fluid conditions. The flow resistance (K) factors for the simple support grids are approximately one third the values for the mixing vane grids. In addition, previous Westinghouse CHF tests (reported in WCAP-7411-1-P-A) were reviewed to determine the effect of the simple support grids on the CHF results. The effects of simple support grids, "T+H mixing vane grids", "mixing vane grids", and "scoop type mixing vane grids" were studied in an eight foot heated test section with 10", 20" and 26" grid spacing.

The effects of simple, minimum resistance grids have also been studied by Babcock & Wilcox (References 6, 7) and Battelle Pacific Northwest Laboratories (Reference 8). These reports generally agree that the turbulent downstream effects of simple grids is eliminated (washed out) within a distance of 8 to 10 inches. Westinghouse fuel designs use mixing vane grid spacings of greater than 20 inches. The CHF tests most closely simulating the fuel design grid spacing were done with 20, 22 and 26-inch grid spacing. For these tests the inclusion of simple support grids half-way between the mixing vane grids results in at least a 10-inch distance between the simple support grid and the CHF location which was generally just upstream of a mixing vane grid. Although there is no direct data on the effect of including simple support grids between the mixing vane grids, the existing data on simple support grids are sufficient to indicate that the effect is small or negligible. Therefore no penalty or uncertainty is required in the correlation to account for this atypicality.

The effect of the number of rods in the CHF tests has been reviewed. The CHF tests indicate that CHF occurs on the interior rods. The subchannel analysis of the CHF tests indicates that the enthalpy gradient across the bundle is very small and the potential for CHF being effected by bundle edge effects is therefore minimal. In addition to these observations, it should be noted that the WRB-1 correlation fits the 3x3 bundle data, the 4x4 bundle data and the 5x5 bundle data reasonably well without the need for any empirical terms related to the number of rods in the bundle.

Staff Positions

The staff has reviewed the subchannel calculations and the other assumptions used in the development of the WRB-1 correlation as well as the atypicalities in the CHF. We conclude that the inclusion of uncertainties for these areas would not significantly alter the WRB-1 correlation or the final DNBR correlation limits. Uncertainties in these areas are therefore not required.

The WRB-1 CHF correlation predicts the CHF test data reasonably well; and the mean value and standard deviation of the Measured CHF/Predicted CHF for each individual test series are acceptable measures of the accuracy of the correlation. We conclude that there is a significant component of variance associated with changes from one test series to another and that this component of variance must be accounted for in the establishment of a DNBR limit. An acceptable method of accounting for this component of variance was previously discussed. Table VI presented the total variance and degrees of freedoms based on that method. The DNBR limits presented in Table VII were calculated using the same technique for establishing the DNBR limit as proposed by Westinghouse. However, the input values of variance, degrees of freedom and correlation mean were taken from Table VI.

The unusually high DNBR limit of 1.37 for the application of the WRB-1 correlation to L-grid fuel is, in part, due to the limited number of L-grid geometries tested. It may also be the result of a difference in the heated length effect for L-grids relative to R-grids, as previously discussed. The staff acknowledges that additional data or additional analytical work on the WRB-1 correlation for L-grid application could substantially improve the results.

Because of the empirical nature of the correlation and because of the additional component of variance among the test series, as previously discussed, we conclude that the mean value, standard deviation and DNBR limit presented in Table VII are appropriate measures of the correlation accuracy; and that the mean value, standard deviation and DNBR limit, proposed by Westinghouse, based on all 1147 data points are not appropriate representations of the correlation accuracy. We find that the WRB-1 correlation is acceptable for use in PWR thermal-hydraulic design with the DNBR correlation limits specified in Table VII.

References

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3. Wheeler, C. L., et al, "COBRA IV-I: An Interim Version of COBRA for Thermal-Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements and Cores", BNWL-1962 March 1976.

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5. Rosal, E. R., Cermak, J. O., Tong, L. S., "Rod Bundle Axial Non-Uniform Heat Flux DNB Tests and Data" WCAP-7411-1-P-A, January 1975

6. Zielhe, L. A., Wilson, R. H., "Transient Critical Heat Flux and Spacer Grid Studies", Nuclear Technology, Volume 24. October 1974.

7. Morgan, C. D., "Correlation of Critical Heat Flux in a Bundle by Pressurized Water" BAW-10036, January 1972.

8. Alberman, R. T., and Rowe, D. S., "An Experimental Study of Turbulent Flow in a Model Babcock & Wilcox Fuel Bundle" PNL Report 212 B00763.

TABLE 1

COMPARISON OF LOCAL COOLANT CONDITIONS

Test No.	Difference in Calculated % Quality* THINC-COBRA III	THINC-COBRA IV
W-1796	-0.6	-0.6
W-17979	-1.0	-1.0
W-1798	-0.4	-0.4
W-1799	-0.4	-0.3
W-1800	-0.1	+0.1
W-1801	+0.1	+0.1
W-1802	+0.4	+0.4
W-1803	-0.1	+0.1
W-1804	-0.4	-0.4
W-1805	-0.8	-0.8
W-1806	-0.1	-0.2
W-1807	-0.6	-0.6
W-1808	0.0	-0.5
W-1809	-0.7	-0.7
W-1810	-0.3	-0.3
W-1811	-0.3	-0.2
W-1812	-0.2	-0.1
W-1813	-0.2	-0.2

*Difference in % Quality = THINC Quality in % - COBRA Quality in %

TABLE II

TYPICAL, LOCAL COOLANT CONDITIONS AT CHF LOCATION FROM COBRA

SUBCHANNEL	ENTHALPY BTU/LB	QUALITY %	MASS FLOW MLB/M FT^2
1	794.8	19.0	2.755
2	793.7	18.8	2.766
3	793.1	18.6	2.773
4	792.8	18.5	2.219
5	792.5	18.4	2.217
6	792.4	18.4	1.961

Typical Comparison of the Test Series Mean Values of Measured CHF/Predicted CHF

Using THINC and COBRA-IV

Table III

Test Series	#Pts	Measured CHF WCAP-8762	Predicted CHF COBRA	Standard Deviation WCAP-8762	COBRA
A-1	71	.9964	.9910	.0655	.0640
A-3	73	1.0502	1.0360	.1020	.0932

Table IV

Typical Comparison of the Test Series Mean Values of Measured CHF/Predicted CHF

Using COBRA III and COBRA IV

Test Series	# Pts	Measured CHF / Predicted CHF COBRA III	COBRA IV	Standard Deviation COBRA III	COBRA IV
A-1	71	.9912	.9910	.0640	.0640

*Test geometry for each series is identified in Table 3-1 of WCAP-8762

Table V

Analysis of Variance Test for CHF Data

Description	Test Series	F Calculated Values	Theoretical F Range at 99% Confidence
All Data	A-1 A-24	11.2	.6 - 1.8
All R grid	A-1 A-19	6.2	.5 - 2.0
All L grid	A-20 A-24	46.4	.3 - 3.3
14' UNIF	A-1, A-2, A-15	15.4	.2 - 4.7
14' COSINE	A-5 A-18	1.05	.2 - 6.9
14' USINU, R Grid	A-9, A-10, A-11 A-12, A-14, A-16 A-17	6.9	.2 - 2.8
14' USINU L Grid	A-21, A-23, A-24	16.3	.2 - 4.7
14' USINU R&L Grid	A-9, A-10, A-11 A-12, A-14, A-16, A-17, A-21, A-23 A-24	8.0	.4 - 2.4
8' UNIF	A-3, A-19, A-4	2.6	.2 - 4.6
14', 5x5 TYP	A-1, A-2, A-5	.2	.2 - 4.6
14', 22" GSP	A-1, A-5, A-18	.1	.2 - 4.6
14', 4x4, TYP, R-Grid	A-9, A-10, A-11 A-12, A-14, A-15	15.7	.3 - 3.0
14', 5x5	A-1, A-2, A-5	.13	.3 - 3.8
14', 5x5, UNIF, TYP	A-1, A-2	.4	.2 - 6.9
8', 5x5, UNIF, TYP	A-3, A-4	.7	.2 - 6.9
5x5, UNIF, TYP	A-1, A-2, A-3, A-4	5.5	.3 - 3.8

TABLE VI

STATISTICS FOR R-GRID AND L-GRID

GRID TYPE	σ_W	σ_A	σ_T	F_T	AVG. M/P
R	0.0819	0.0298	0.0871	633	1.0084
L	0.0647	0.0719	0.0968	13	0.9818

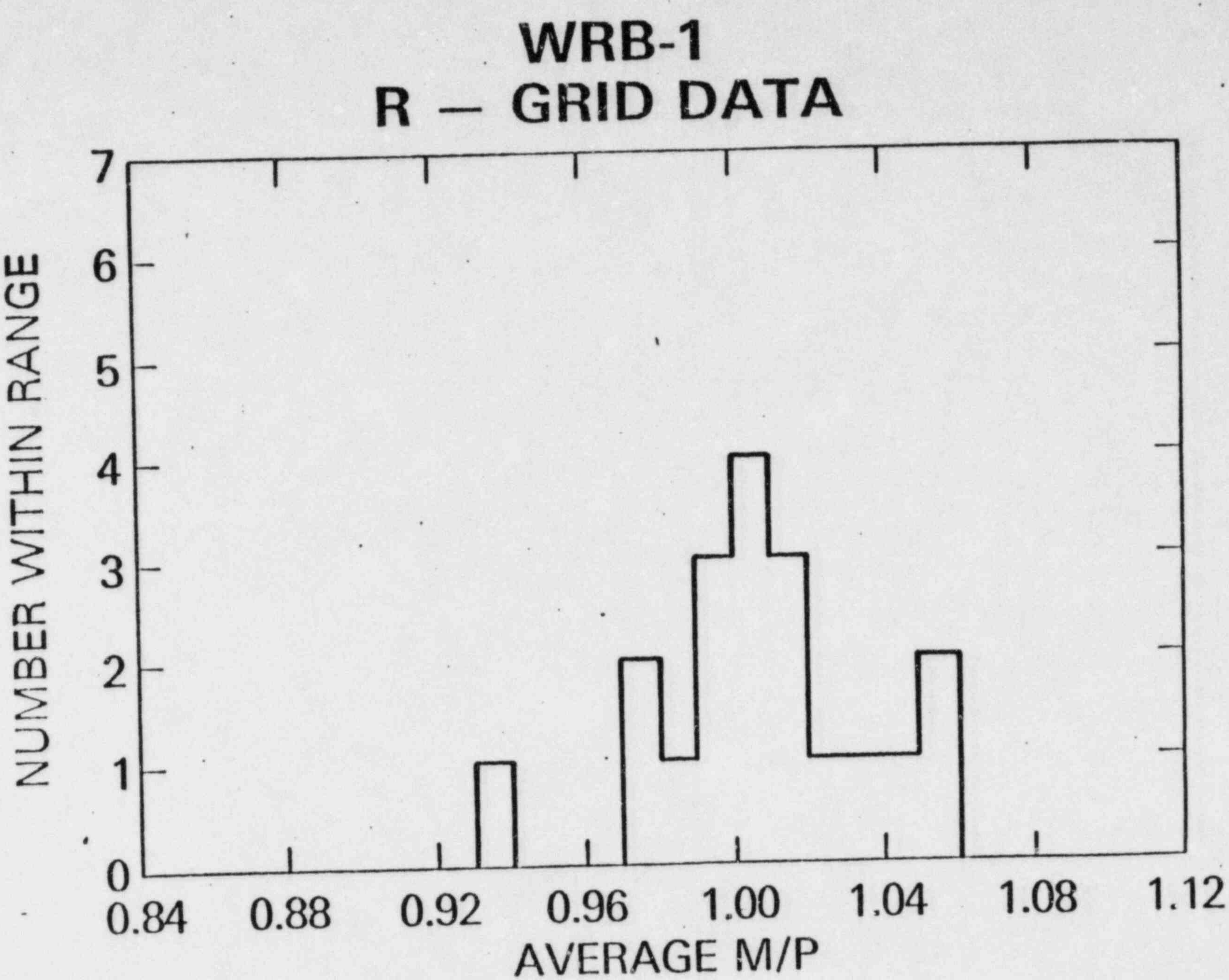
$$\sigma_T^2 = \sigma_W^2 + \sigma_A^2$$

$$F_T = \left(\sum_{i=w}^{A} \sigma_i^2 \right)^2 \Big/ \sum_{i=w}^{A} \sigma_i^4 / f_i$$

TABLE VII

ACCEPTABLE PWR FUEL DESIGN, DNBR LIMITS

FUEL DESIGN	APPLICABLE TEST SERIES	DNBR LIMIT
17 x 17 R GRID 14' LENGTH	A-1, A-2, A-5, A-18	1.17
17 x 17 R GRID 12' LENGTH	A-1, A-2, A-5, A-18 A-3, A-4, A-19	1.17
15 x 15 R GRID 12' LENGTH	A-6, A-7, A-8, A-9, A-10, A-11, A-12, A-13, A-14, A-15, A-16, A-17	1.17
15 x 15 L GRID 12' LENGTH	A-20, A-21, A-22, A-23, A-24	1.37
14 x 14 L GRID 12' LENGTH		1.37


WRB-1
R — GRID DATA
NUMBER WITHIN RANGE
0
1
2
3
4
5
6
7
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
AVERAGE M/P
Figure 1

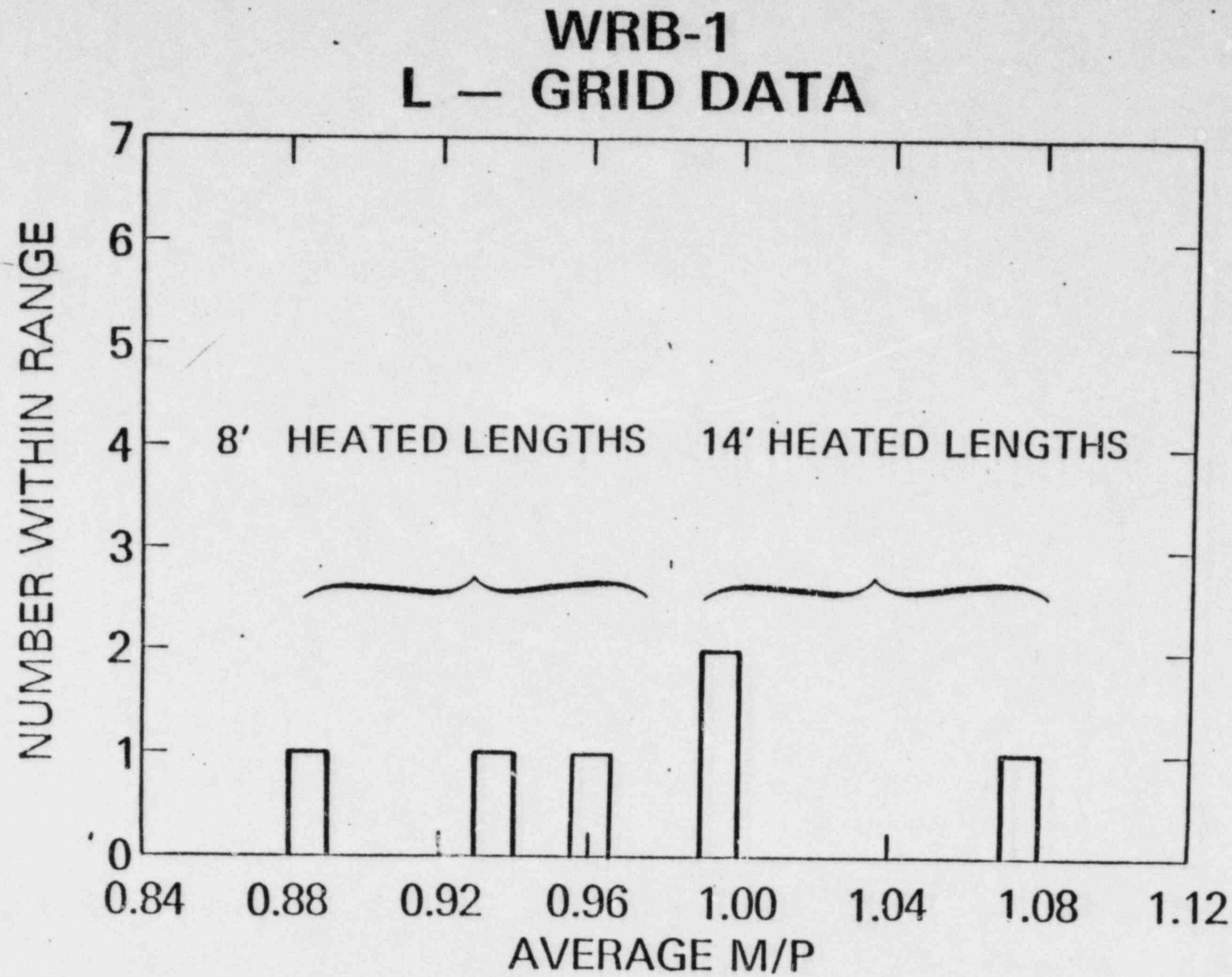

WRB-1
L — GRID DATA
NUMBER WITHIN RANGE
0
1
2
3
4
5
6
7
8' HEATED LENGTHS
14' HEATED LENGTHS
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
AVERAGE M/P

Figure 2

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 29 1984

Mr. E. P. Rahe, Jr., Manager
Nuclear Safety Department
Water Reactor Divisions
Westinghouse Electric Corporation
P. O. Box 355
Pittsburg, Pennsylvania 15230

Dear Mr. Rahe:

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT - WCAP-8762(P)/WCAP-8763(NP), SUPPLEMENT 1, "BASIS FOR THE APPLICABILITY OF THE WRB-1 CORRELATION TO 15 x 15 OFA AND 14 x 14 OFA FUEL"

We have completed our review of the subject topical report submitted November 18, 1983, by Westinghouse Electric Corporation. We find the report to be acceptable for referencing in license applications to the extent specified and under the limitations delineated in the report and the associated NRC evaluation, which is enclosed. The evaluation defines the basis for acceptance of the report.

We do not intend to repeat our review of the matters described in the report and found acceptable when the report appears as a reference in license applications, except to assure that the material presented in applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that Westinghouse publish accepted versions of this report, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an A (designating accepted) following the report identification symbol.

Should our criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, Westinghouse and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Cecil O. Thomas

Cecil O. Thomas, Chief
Standardization and Special
Projects Branch
Division of Licensing

Enclosure: As stated

ENCLOSURE

WCAP-8762(P)/WCAP-8763(NP)

SER ON THE APPLICABILITY OF WRB-1 TO WESTINGHOUSE 14X14 AND 15X15

1. INTRODUCTION AND BACKGROUND

The Westinghouse rod bundle critical heat flux (CHF) correlation, WRB-1, has prevously been approved (Ref. 1,2) for application to the 15x15 and 17x17 standard low parasitic (LOPAR) fuel assemblies and 17x17 optimized fuel assemblies (OFA). The approved minimum departure from nucleate boiling ratios (DNBR) are 1.17 for the standard R-type mixing vane grid assembly and the 17x17 OFA, and 1.37 for the standard L-Grid assembly. By letter dated November 18, 1983 (Ref. 3), Westinghouse submitted Supplement 1 to WCAP-8762, "Basis for the Applicability of the WRB-1 correlation to 15x15 and 14x14 OFA Fuel," to apply for the extension of the application of WRB-1 to the 14x14 and 15x15 OFA with a DNBR limit of 1.17.

The differences between the OFA and standard LOPAR fuel are the fuel pin diameters and the mixing vane spacer grid designs. The 17x17 OFA has a pin outer diameter of 0.36 inches versus 0.374 inches for the standard 17x17 fuel; the 14x14 OFA and 15x15 OFA have pin diameters of 0.40 inches and 0.422 inches, respectively, compared to 0.422 inches for both 14x14 and 15x15 standard fuel. The OFA spacer grid has thicker and higher straps made of Zircaloy having different mechanical properties than the Inconel straps used in the standard grids. Although the OFA grid dimensions are different than the standard LOPAR grid, Westinghouse stated that there is no significant departure from the type-R grid characteristics.

The WRB-1 correlation as described in WCAP-8762 (Ref. 4) was orginally approved for application to the 17x17 and 15x15 standard fuel assemblies based on the available CHF test data representative of standard fuel.

In order to extend the application of WRB-1 to the 17x17 OFA, Westinghouse in its submittal WCAP-9401 (Ref. 5) provided additional CHF test data from a test assembly representative of the 17x17 OFA. To justify that the DNBR limit of 1.17 is applicable to the 17x17 OFA, a statistical analysis was performed to show that the OFA data belong to the same population as the standard R-grid data. The result of this analysis showed that the OFA data were within the tolerance limits of the means of the measured to predicted CHF ratios (M/P) of the comparable standard R-grid data. The analysis of variances showed that the null hypothesis, that the variances of the M/P ratios of the OFA typical cell and standard R-grid typical cell are equal, would not be rejected at a 5 percent significance level. For the OFA thimble cell data, a similar hypothesis would be rejected at a 5 percent significance level. However, since the rejected OFA data had a lower standard deviation, it was shown that a DNBR limit of 1.17 would be conservative when applied to the rejected data. Based on this analysis, WRB-1 was found acceptable for application to the 17x17 OFA with the same DNBR limit of 1.17.

The extension of the WRB-1 applicability to the 14x14 and 15x15 OFA will be evaluated and discussed in the following section.

2. STAFF EVALUATION

In order to justify the extension of the applicability of WRB-1 to the 14x14 and 15x15 OFA, Westinghouse provided additional CHF test data from the test bundle representative of the 14x14 OFA. Westinghouse maintains that the same DNBR limit of 1.17 for the standard R-grid fuel is also applicable to the 14x14 and 15x15 OFAs. To justify this assertion, it must be shown that the 14x14 OFA data belong to the same population which was used to determine the limit, or that 1.17 was a conservative limit relative to any limit based on the OFA data. In addition, since there is no CHF data representative of the 15x15 OFA, it is necessary that the 15x15 OFA geometry is within the WRB-1 applicability range.

In order to show that the 14x14 OFA test data belong to the same population as the standard fuel data, Westinghouse has performed a statistical analysis of the measured to predicted CHF ratios from the 14x14 OFA test data and the comparable standard R-grid data with fuel OD of 0.422 inches. The analysis consists of a F-test for equality of population variances and a t-test for equality of population means. The results show that both null hypotheses of equal variances and means of the 14x14 OFA and the comparable standard R-grid data distributions cannot be rejected at a 5 percent significance level. In this analysis, Westinghouse has combined the 2 sets of standard R-grid data having 0.422 inches pin diameter and 26 inches grid spacing into one group and therefore the tests of variances and means are simply two group analyses between the standard and OFA data. The st ff has performed a one way analysis of variances for the equality of means test as an independent check. In this calculation, the standard R-grid data are not combined into one group. The result of this staff analysis of variance also shows that the null hypothesis of equal means cannot be rejected at 5 percent significance level. Therefore, the 14x14 OFA CHF data can be incorporated into the total R-grid population. Using the mean and standard deviation of the (M/P) ratios corresponding to the combined total data, the derived one-sided tolerance minimum DNBR limit would be 1.163 with 95 percent probability at a 95 percent confidence level of avoiding DNB. In addition, the 95/95 DNBR limit derived from the 14x14 OFA data alone would be 1.122. These DNBR limits are below the proposed 1.17. Therefore, the staff concludes that WRB-1 is applicable to the 14x14 OFA with a DNBR limit of 1.17.

The 15x15 OFA design is virtually identical to the 15x15 R-grid design except for the spacer grid dimensions. In order to minimize the effect of the grid dimensional changes on DNB performance, Westinghouse stated that special care was taken in the OFA grid design to preserve the important mixing vane characteristics, flow area ratio, and the dimple and spring arrangement used for maintaining the grid-to-rod contact. The success of the use of this scaling technique in the OFA grid design has been demonstrated by the fact that WRB-1 predicts both 17x17 and 14x14 OFA CHF data well without any modification to the correlation. Repeatability studies performed as described in WCAP-9401 have shown that the WRB-1 correlation's prediction capability is essentially identical for both OFA and standard fuel geometry, indicating no additional component of variance is introduced by the grid dimensional change. In other words, the correlation correctly accounts for the equivalent diameter effects and the scaling approach for the grid dimensional changes.

Since the 15x15 OFA diameter, rod pitch, heated length and grid spacing are within the WRB-1 applicability range and the success of the scaling technique in the OFA mixing vane grid design has been proved by the similar 14x14 and 17x17 OFA grid design, we conclude that WRB-1 is also applicable to the 15x15 OFA with a DNBR limit of 1.17.

3. REGULATORY POSITION

The staff has reviewed Supplement 1 to WCAP-8762. We find that the WRB-1 correlation is acceptable for application to both 14x14 OFA and 15x15 OFA with a minimum DNBR limit of 1.17. This acceptability is subject to other restrictions which were imposed in the staff safety evaluation reports (Refs. 1 and 2) on WCAP-8762 and WCAP-9401.

REFERENCES

1. Memorandum from D. F. Ross, Jr. (NRC) to D. B. Vassallo (NRC), "Topical Report Evaluation for WCAP-8762," April 10, 1978.

2. Letter from R. L. Tedesco (NRC) to T. M. Anderson (Westinghouse), "Acceptance for Referencing Topical Report WCAP-9401(P)/WCAP-9402 (NP)," May 7, 1981.

3. Letter from E. P. Rahe, Jr. (Westinghouse) to C. O. Thomas (NRC), "Basis for Applicability of the WRB-1 CHF Correlation to 15x15 OFA and 14x14 OFA Fuel, Supplement 1, WCAP-8762," NS-EPR-2854, November 18, 1983.

4. F. E. Motley, et al, "New Westinghouse Correlation WRB-1 For Predicting Critical Heat Flux In Rod Bundles With Mixing Vane Grids," Westinghouse Topical Report WCAP-8762, July 1976.

5. M. D. Beaumont and J. Skaritka, "Verification Testing and Analyses of the 17x17 Optimized Fuel Assembly," WCAP-9401, March 1979.

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LIST OF ILLUSTRATIONS

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ACKNOWLEDGMENT

The authors wish to thank Mr. Jeffry Hoffman who developed the flexible and sophisticated computer techniques used in developing this correlation.

ABSTRACT

A new critical heat flux (CHF) correlation, based on local fluid conditions, has been developed from Westinghouse rod bundle data. This correlation applies to both 0.422 inch and 0.374 inch rod O. D., geometries. It accounts for typical cell and thimble cell effects, uniform and non-uniform heat flux profiles, variations in rod heated length and in grid spacing. The applicable range of variables is:

Pressure	$1440 \leq P \leq 2490$ psia
Local Mass Velocity	$0.9 \leq G_{loc}/10^6 \leq 3.7$ lb/ft^2-hr
Local Quality	$-0.2 \leq X_{loc} \leq 0.3$
Heated Length, Inlet to CHF Location	$L_h \leq 14$ feet
Grid Spacing	$13 \leq g_{sp} \leq 32$ inches
Equivalent Hydraulic Diameter	$0.37 \leq d_e \leq 0.60$ inches
Equivalent Heated Hydraulic Diameter	$0.46 \leq d_h \leq 0.58$ inches

The correlation predicts CHF for 1147 data points with a sample mean and standard deviation of measured-to-predicted heat flux ratio of 1.0043 and 0.0873, respectively.

It was concluded that to meet the reactor design criterion the minimum DNBR should be 1.17.

The new CHF correlation in the above range of applicability is intended to supercede correlations presently in use for Westinghouse cores employing the "L" and "R" - grid fuel assembly designs.

The name *WRB-1* (for *"Westinghouse Rod Bundle"*) has been selected for this new correlation.

SECTION 1
INTRODUCTION

The W-3 correlation, and several modifications of it, are presently used for all Westinghouse CHF calculations. The W-3 was originally developed from single tube data,[1] but was subsequently modified to apply to the 0.422 inch O. D. rod "R"-grid,[2] and "L"-grid,[3] as well as the 0.374 inch O. D.,[4,5] rod bundle data. These modifications to the W-3 correlation have been demonstrated to be adequate for reactor rod bundle design.

However, it has been felt that a new correlation could be developed based exclusively on the large bank of mixing vane grid rod bundle CHF data (over 1100 points) that Westinghouse has collected in recent years. Such a new correlation would, ideally, represent these data with better accuracy over a wider range of variables. It is the purpose of this report to describe the development of such a correlation, which has been named the *WRB-1* correlation.

---

1. L. S. Tong, "Boiling Crisis and Critical Heat Flux", TID-25887, 1972.
2. F. E. Motley, F. F. Cadek, "DNB Test Results for New Mixing Vane Grids (R), WCAP-7958-A, January, 1975.
3. F. E. Motley, F. F. Cadek, "Application of Modified Spacer Factor to L Grid Typical and Cold Wall Cell DNB", WCAP-8030-A, October, 1972.
4. F. E. Motley, A. H. Wenzel, F. F. Cadek, "Critical Heat Flux Testing of 17 x 17 Fuel Assembly Geometry with 22 inch Grid Spacing", WCAP-8537, May, 1975.
5. K. W. Hill, F. E. Motley, F. F. Cadek, A. H. Wenzel, "Effect of 17 x 17 Fuel Assembly Geometry on DNB", WCAP-8297-A, February, 1975.

SECTION 2
ORIGIN OF THE CORRELATION

The development of the correlation started by considering data from individual test geometries one at a time to establish the basic relationships between the flow parameters. Different test geometries were then added, one by one, in an orderly fashion to identify and correlate the effects of test section length, grid spacing, D_e, D_h, and grid type. The details of this step-by-step process are as follows:

1) *Basic Form of the Correlation*

The development of the new CHF correlation was based on the evaluation of local fluid conditions as determined by the THINC sub-channel computer code. Inspection of the data from the 0.374 inch rod O. D. uniformly heated tests indicated that there exists a linear relationship between CHF heat flux and local quality (X_{LOC}):

$$q''_{CHF} = A - BX_{LOC}$$

This relationship is entirely empirical, but it has been observed by many different experimentors, as discussed in reference.[1] It applies quite well to Westinghouse mixing vane grid data.

2) *Identification of Parameter Dependence of Empirical Functions A and B*

Figure 2-1 shows a large number of lines plotted on the q''_{CHF} versus X_{LOC} plane; each line is from a linear regression fit of several runs carried out with the same test section conditions of constant pressure and flow. Inspection of figure 2-1, and of other similar plots for other test geometries, shows similar trends with respect to the functional variations of the "constants" A and B. After extensive trial and error fitting, it was concluded that:

$$A = A(P, G_{LOC}, L_H, g_{SP}, d_g)$$

$$B = B(P, G_{LOC}, L_H)$$

where: P = pressure (psia)

1. P. G. Barnett, "An investigation into the Validity of Certain Hypotheses Implied by Various Burnout Correlations", AEEW-R214, June, 1963.

FITS ARE FROM 14 FT, 0.374 INCH ROD O.D.,
UNIFORM, TYPICAL CELL TEST SECTIONS WITH
22 INCH GRID SPACING

SYMBOL	PRESSURE PSIA	$G_{LOC}/10^6$, LB/HR-FT^2
A	1500	2.5
B	1500	3.5
C	1800	1.5
D	1800	2.5
E	1800	3.5
F	2100	1.5
G	2100	2.5
H	2100	3.5
I	2400	1.5
J	2400	3.5

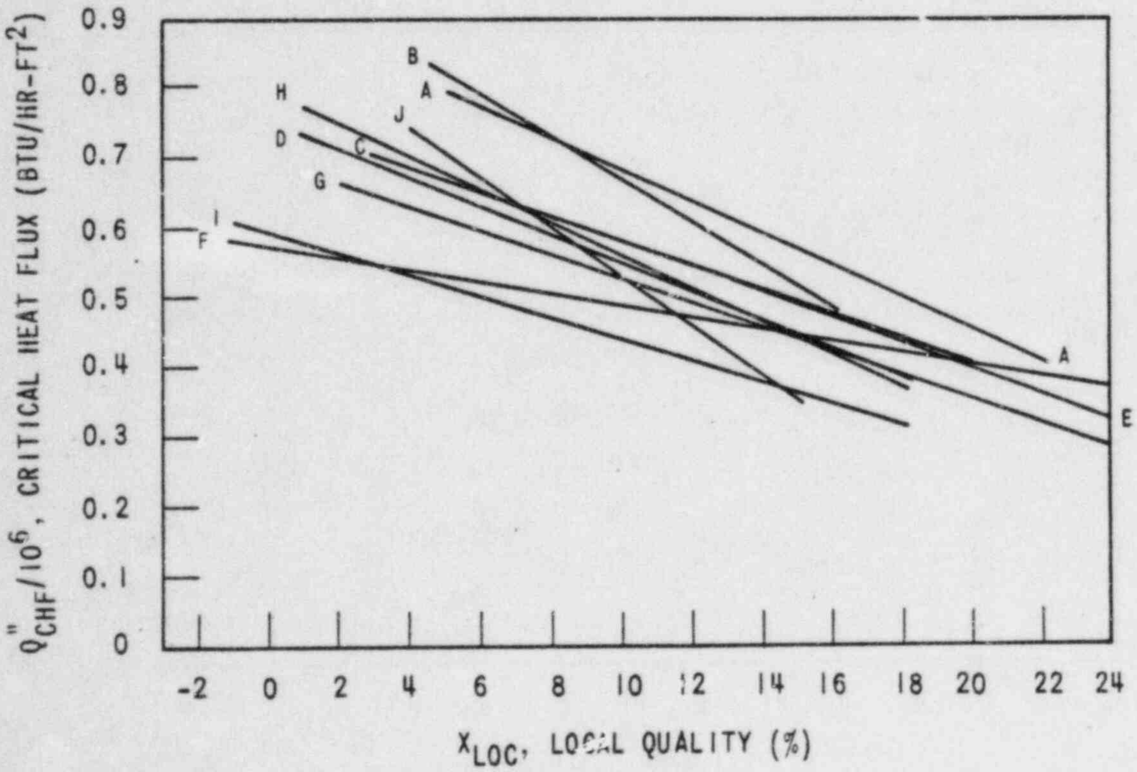

Figure 2-1. Typical Fits of the Form $Q''_{CHF} = A - BX_{LOC}$ with Westinghouse Mixing Vane Grid Data

G_{LOC} = local mass velocity (lb/ft^2-hr)

L_H = heated length, inlet to CHF location (feet)

g_{SP} = grid spacing (inches)

d_g = distance from last grid to CHF site (inches)

3) *Basic Form of Correlation Based on 0.374 Inch Rod O. D. Uniformly Heated Typical Cell Data*

In the development of the correlation, the initial formulation of the A and B functions was based first only on four sets of 0.374 inch rod O. D. axially uniform heat flux typical cell data. This resulted in an evaluation of A and B which applied to uniformly heated, typical cell data, and included heated length, grid spacing, and distance from the last grid to the site of CHF.

In the evaluation of the coefficients, the conditions at the actual measured CHF location for each uniform heat flux point were used. In cases where CHF was indicated at two elevations, conditions at both elevations were included. An extensive discussion of this approach is given in reference.[1]

The new form of the correlation contains the distance from the last grid to the CHF site as a parameter. The addition of this parameter to the correlation enables it to provide about 93 percent agreement between the measured and predicted CHF elevation. This will be discussed in more detail in section 3-4.

4) *Confirmation of the Existing Non-Uniform F-factor*

Once a form was developed which represented the uniformly heated data, the CHF correlation was applied to the 0.374 inch rod O. D. non-uniform typical cell data, using the non-uniform F-factor.[2] The derivation given in that reference is from theoretical considerations, and is thus an analytical form, except for a single "constant" which must be evaluated utilizing the test data. The formulation of this constant (actually a function of local conditions) is given in reference.[2] Comparison with non-uniform data indicated that no modification to either the constant or the form of the F-factor was necessary for the present application.

1. F. E. Motley, A. H. Wenzel, F. F. Cadek, "Critical Heat Flux Testing of 17 x 17 Fuel Assembly Geometry with 22 inch Grid Spacing", WCAP-8537, May, 1975.
2. L. S. Tong, "Boiling Crisis and Critical Heat Flux", TID-25887, 1972.

5) *Extension of Correlation to Other Rod Bundle Geometries*

With the confirmation that the form of the F-factor of reference[1] was satisfactory when used with the new form of the correlation, the new correlation was then extended to the large body of Westinghouse data taken with 0.422 inch rod O. D. non-uniform axial heat flux test sections. This extension required the addition of several new constants to the correlation in order to account for the differences in test section geometry. These geometry effects are expressed by terms incorporating D_e and D_h (hydraulic and heated hydraulic equivalent diameters). The much wider range of grid spacing available with this 0.422 inch data necessitated a modification in the form of the grid spacing term.

Once the geometry differences had been accounted for with typical cell data, the new correlation was then extended to thimble cell data. This resulted in further modification of the D_e and D_h terms so that the revised form could apply to both typical and thimble cell geometries.

6) *Formulation of Performance Factor (PF)*

The above formulation fit the data well, but it required a performance factor (PF) to yield the proper trend with D_e and D_h in going from the 0.422 inch rod O. D. to the 0.374 inch rod O. D. data. This allowed the correlation to simulate the slight change in the geometry of the mixing vane between the 0.422 inch and the 0.374 inch O. D. rod bundle geometry.

In order to assure the proper D_e trend independent of the performance factor, an additional set of 0.500 inch O. D. rod data with mixing vanes scaled from the 0.422 inch mixing vane shape was added to the total data set.

7) *Final Form of Correlation*

The final form of *WRB-1* correlation, which meets all the criteria discussed above, is given on the following page.

---

1. L. S. Tong, "Boiling Crisis and Critical Heat Flux", TID-25887, 1972.

WRB-1 CHF CORRELATION

$$\frac{q''_{CHF}}{10^6} = PF + A_1 + B_3 \frac{(G_{LOC})}{10^6} - B_4 \frac{(G_{LOC})}{10^6} X_{LOC}$$

$$PF = \left[\quad \right] \begin{matrix} \text{for 0.422 inch O. D. Rods} \\ \text{for 0.374 inch O. D. Rods} \end{matrix} \quad (a,c)$$

A_1 =

B_3 =

B_4 = (a,c)

(a,c)

RANGE OF VARIABLES

Pressure	$1440 \leq P \leq 2490$ psia
Local Mass Velocity	$0.9 \leq G_{loc}/10^6 \leq 3.7$ lb/ft^2-hr
Local Quality	$-0.2 \leq X_{loc} \leq 0.3$
Heated Length, Inlet to CHF Location	$L_h \leq 14$ feet
Grid Spacing	$13 \leq g_{sp} \leq 32$ inches
Equivalent Hydraulic Diameter	$0.37 \leq d_e \leq 0.60$ inches
Equivalent Heated Hydraulic Diameter	$0.46 \leq d_h \leq 0.58$ inches

SECTION 3
STATISTICS

3-1. SOURCES OF DATA

Westinghouse, over a period of about six years, has collected a large body of rod bundle CHF data - over 1100 runs - using full-scale, electrically-heated rod bundle test sections. All of these tests were carried out at the Columbia University Heat Transfer Laboratory. A complete description of the Columbia University test facilities, and of the general procedures followed in conducting these tests, is given in reference.[1]

Table 3-1 summarizes the various bodies of data used in developing the *WRB-1* correlation. Most, but not all, of these data sets have been published previously; the appropriate references are given in table 3-1. However, all the data - whether previously published or not - are given in the appendix of this report.[2]

3-2. TEST SECTION CHARACTERISTICS

The references given in table 3-1 contain detailed descriptions of the various test sections used to obtain these data, but a brief summary of their pertinent characteristics is given below for convenience.

All of the test sections were either 8 or 14 feet in heated length. The axial heat flux profiles were either uniform or non-uniform; the non-uniform test sections had either a cosine or a usinu axial heat flux profile. Figure 3-1 shows the shapes of the various axial heat flux profiles that have been tested.

Figure 3-2 is a sketch of the various test geometry cross sections from which the data were obtained.

These test sections were all in the form of rectangular array rod bundles; 5 x 5 for the 0.374 inch rod O. D. test sections, all of which used "R" type grids: and 4 x 4 for the 0.422 inch rod O. D. test sections, which used either "R" or "L" grids.[3] The test sections simulated

1. K. W. Hill, F. E. Motley, F. F. Cadek, A. H. Wenzel, "Effect of 17 x 17 Fuel Assembly Geometry on DNB", WCAP-8297-A, February, 1975.
2. It should be noted that many of the previously reported sets contain substantially more data points than have been reported before. This is because in the past data with qualities above the W-3 quality limit, usually taken to be 15 percent, were eliminated.
3. The 0.500 inch rod O. D. data points included in this study were taken with a 3 x 3 test section which was otherwise similar to other typical cell "L" grid rod bundles.

TABLE 3-1

WRB-1 CHF CORRELATION – STATISTICAL RESULTS

	Rod O. D. Inch	L_H ft	g_{sp} Inch	Heat Flux Profile	Configuration[a]	N	$(\frac{M}{P})$ AVG	Sample Standard Deviation, S	Reference	Appendix Table
"R"	0.374	14	22	UNIF	TYP – 5X5	71	0.9964	0.0655	[1]	A- 1
Grid	0.374	14	26	UNIF	TYP – 5X5	73	1.0041	0.0805	[2]	A- 2
	0.374	8	22	UNIF	TYP – 5X5	67	1.0502	0.1020	[1]	A- 3
	0.374	8	26	UNIF	TYP – 5X5	78	1.0136	0.0848	[2]	A- 4
	0.374	14	22	COSINE	TYP – 5X5	74	1.0022	0.0852	[1]	A- 5
	0.422	8	20	COSINE	TYP – 4X4	33	1.0042	0.0528	[3]	A- 6
	0.422	8	20	USINU	TYP – 4X4	33	0.9937	0.0649	[3]	A- 7
	0.422	8	26	USINU	TYP – 4X4	36	0.9846	0.0922	[3]	A- 8
	0.422	14	26	USINU	TYP – 4X4	35	1.0584	0.0816	[4],[3]	A- 9
	0.422	14	20	USINU	TYP – 4X4	36	1.0100	0.09[illegible]5	[b]	A-10
	0.422	14	13	USINU	TYP – 4X4	38	0.9737	0.0781	[b]	A-11
	0.422	14	32	USINU	TYP – 4X4	38	1.0238	0.0752	[3]	A-12
	0.422	8	32	USINU	TYP – 4X4	31	0.9913	0.0724	[3]	A-13
	0.422	14	26	USINU	TYP – 4X4	71	1.0466	0.0829	[4]	A-14
	0.422	14	26	UNIF	TYP – 4X4	42	0.9321	0.0595	[2]	A-15
	0.422	14	26	USINU	TH – 4X4	39	1.0141	0.0579	[5]	A-16
	0.422	14	32	USINU	TH – 4X4	37	0.9728	0.0887	[5]	A-17
	0.374	14	22	COSINE	TH – 5X5	70	1.0002	0.0796	[1]	A-18
	0.374	8	26	UNIF	TH – 5X5	68	1.0303	0.1048	[2]	A-19
"L"	0.422	8	26	COSINE	TYP – 4X4	36	0.8826	0.0369	[6]	A-20
Grid	0.422	14	26	USINU	TYP – 4X4	41	1.0743	0.0740	[7]	A-21
	0.422	8	20	USINU	TYP – 4X4	29	0.9379	0.0733	[6]	A-22
	0.422	14	26	USINU	TH – 4X4	38	0.9998	0.0728	[7]	A-23
	0.500	14	20	USINU	TYP – 3X3	33	0.9934	0.0581	[6]	A-24
			All DATA			1147	1.0043	0.0873		

a. TYP – Typical Cell
TH – Thimble Cell

b. Not Previously Published

TABLE 3-1 (cont)

WRB-1 CHF CORRELATION – **STATISTICAL RESULTS**

1. Motley, F. E., Wenzel, A. H., and Cadek, F. F., "Critical Heat Flux Testing of 17 x 17 Fuel Assembly Geometry with 22-Inch Grid Spacing," WCAP-8537, May, 1975.

2. Hill, K. W., Motley, F. E., Cadek, F. F., and Wenzel, A. H., "Effect of 17 x 17 Fuel Assembly Geometry on DNB", WCAP-8297-A, February, 1975.

3. Motley, F. E., and Cadek, F. F., "DNB Test Results for New Mixing Vane Grids (R)," WCAP-7958-A, January, 1975.

4. Hill, K. W., Motley, F. E., and Cadek, F. F., "Evaluation of DNB Test Repeatability," WCAP-8201, July, 1973.

5. Motley, F. E., and Cadek, F. F., "DNB Test Results for R Grid Thimble Cold Wall Cells, WCAP-7958-A1-A, January, 1975.

6. Rosal, E. R., Cermak, J. O., and Tong, L. S., "Rod Bundle Axial Nonuniform Heat Flux DNB Tests and Data," WCAP-7411, December, 1969.

7. Motley, F. E., and Cadek, F. F., "Application of Modified Spacer Factor to L-Grid Typical and Cold Wall Cell DNB," WCAP-8030, October, 1972.

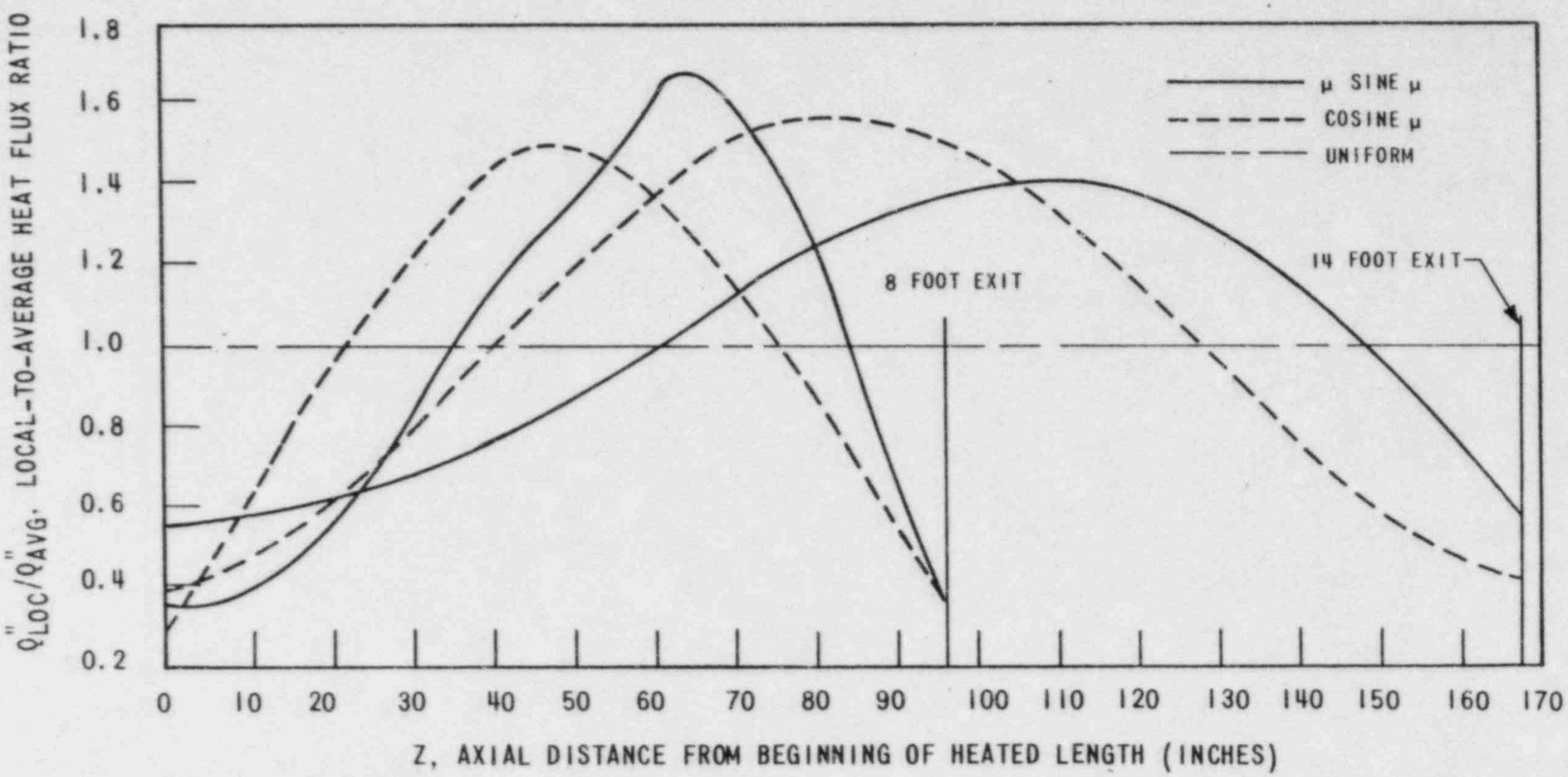

Figure 3-1. 8 Foot and 14 Foot Heater Rods Axial Heat Flux Distributions

10.235-2

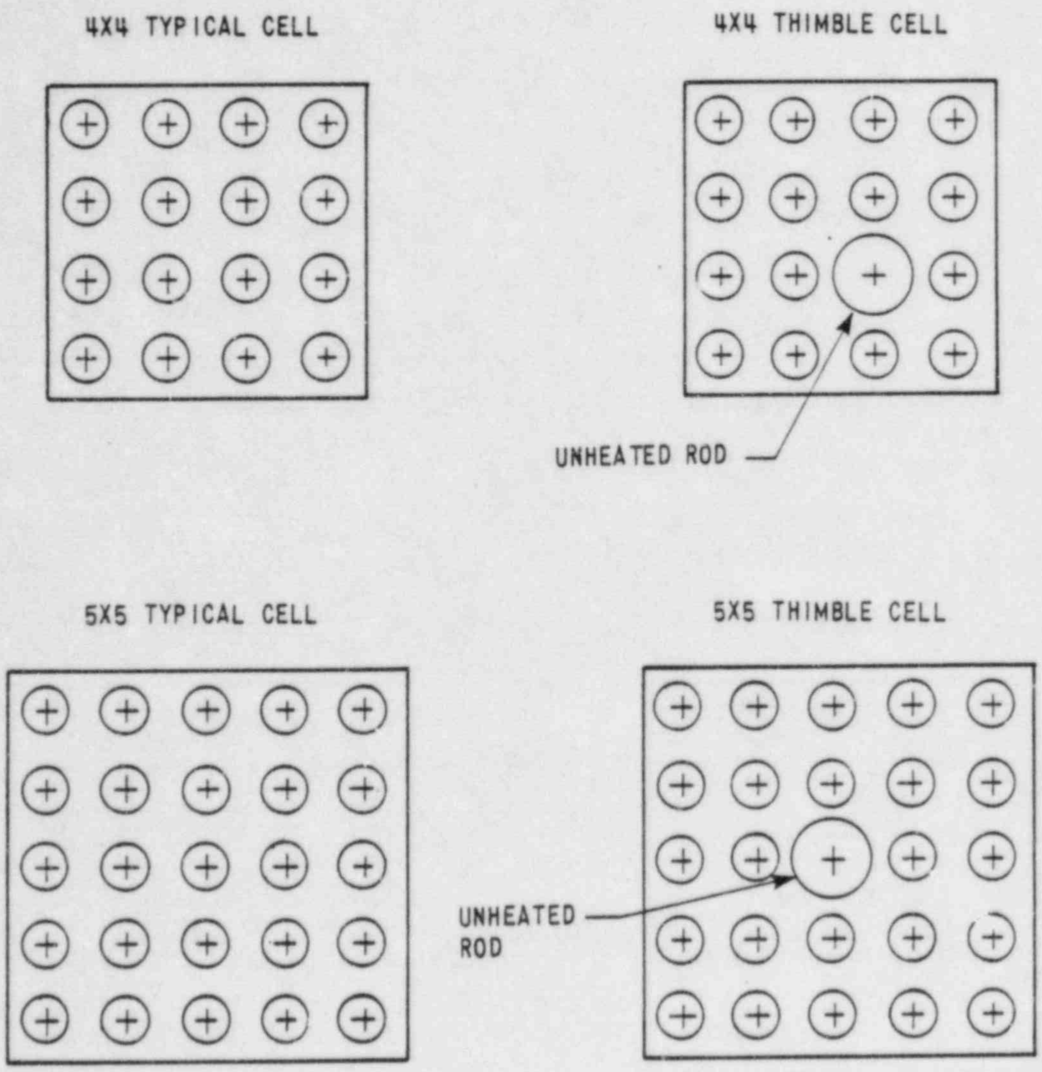

Figure 3-2. Cross-Sections of CHF Test Sections

either a typical cell (all rods heated) or a coldwall cell (i.e., one interior rod unheated, simulating a control rod thimble tube).

3-3. Statistical Results

Table 3-1 gives the results of applying the *WRB-1* correlation to each of the various rod bundle sets, in the form of an average measured-to-predicted critical heat flux ratio, $(M/P)_{AVG}$ and sample standard deviation, s, for each data set. The individual M/P's were evaluated at the point of minimum DNBR, which is defined as:

$$DNBR = (q''_{CHF})_{PRED}/(q''_{CHF})_{MEAS}$$

3-4. Prediction of CHF Location

An unusual feature of the new CHF correlation is the incorporation of a grid spacing term g_{SP}, and of a term which represents the distance to the point of CHF from the last mixing vane grid, d_g. The inclusion of these terms permits a more accurate prediction of the CHF location (the position of minimum predicted-to-measured heat flux ratio). The accuracy of these predicted locations is given in the following table.

TABLE 3-2

ACCURACY OF CHF LOCATION PREDICTIONS

Data Group	Correct Predictions[a]
All Uniform	92.7%
All Non-uniform	75.8%
All	81.7%

a. Based on a 4 percent band for agreement in M/P. This means that if the minimum DNBR location and the measured location are within 4 percent in the value of M/P, they are considered to be in agreement. The 4 percent bandwidth is based on the repeatability study reported in reference,[1] which showed that 4 percent is the standard deviation for repeatability of Westinghouse CHF tests.

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1. K. W. Hill, F. E. Motley, "Evaluation of DNB Test Repeatability", WCAP-8201, July, 1973.

The accuracy of these predictions is most significant with respect to the uniform heat flux data. For the non-uniform data, the exact axial location of CHF is not significant in terms of predictive capability of rod bundle or reactor core power level at CHF. This is discussed in detail in[1].

3-5. Data Plots

Figures 3-3 through 3-6 show the results of applying this correlation to all of the data. Figure 3-3 shows measured critical heat flux plotted against predicted for the 1147 data points. Figures 3-4, 3-5, and 3-6 show M/P (measured-to-predicted heat flux ratio) plotted against fluid parameters - pressure, flow and quality. The low scatter ($s = 0.0873$) in the data and the absence of any significant trend with the fluid parameters indicates that the *WRB-1* correlation accounts quite well for the behavior of these fluid parameters.

3-6. Design Criterion

For the design of Westinghouse reactor cores, the chosen criterion is that CHF will not occur at a 95 percent probability with a 95 percent confidence level. In order to meet this criterion, a limiting value of DNBR is determined by the method of Owen.[2] Owen has prepared tables which give values of k_p such that at least a proportion P of the population is greater than $(\frac{M}{P})_{AVG} - k_p s$ with confidence γ where $(\frac{M}{P})_{AVG}$ and s are the sample mean and standard deviation, respectively. When this method was carried out using all 1147 data points, the results indicate that a reactor core designed using the *WRB-1* correlation could operate with a minimum DNBR of 1.17 and satisfy the design criterion.

1. F. E. Motley, A. H. Wenzel, F. F. Cadek, "Critical Heat Flux Testing of 17 x 17 Fuel Assembly Geometry with 22 inch Grid Spacing", WCAP-8537, May, 1975.

2. D. B. Owen, "Factors for One-Sided Tolerance Limits and for Variable Sampling Plans", SCR-607, March, 1963.

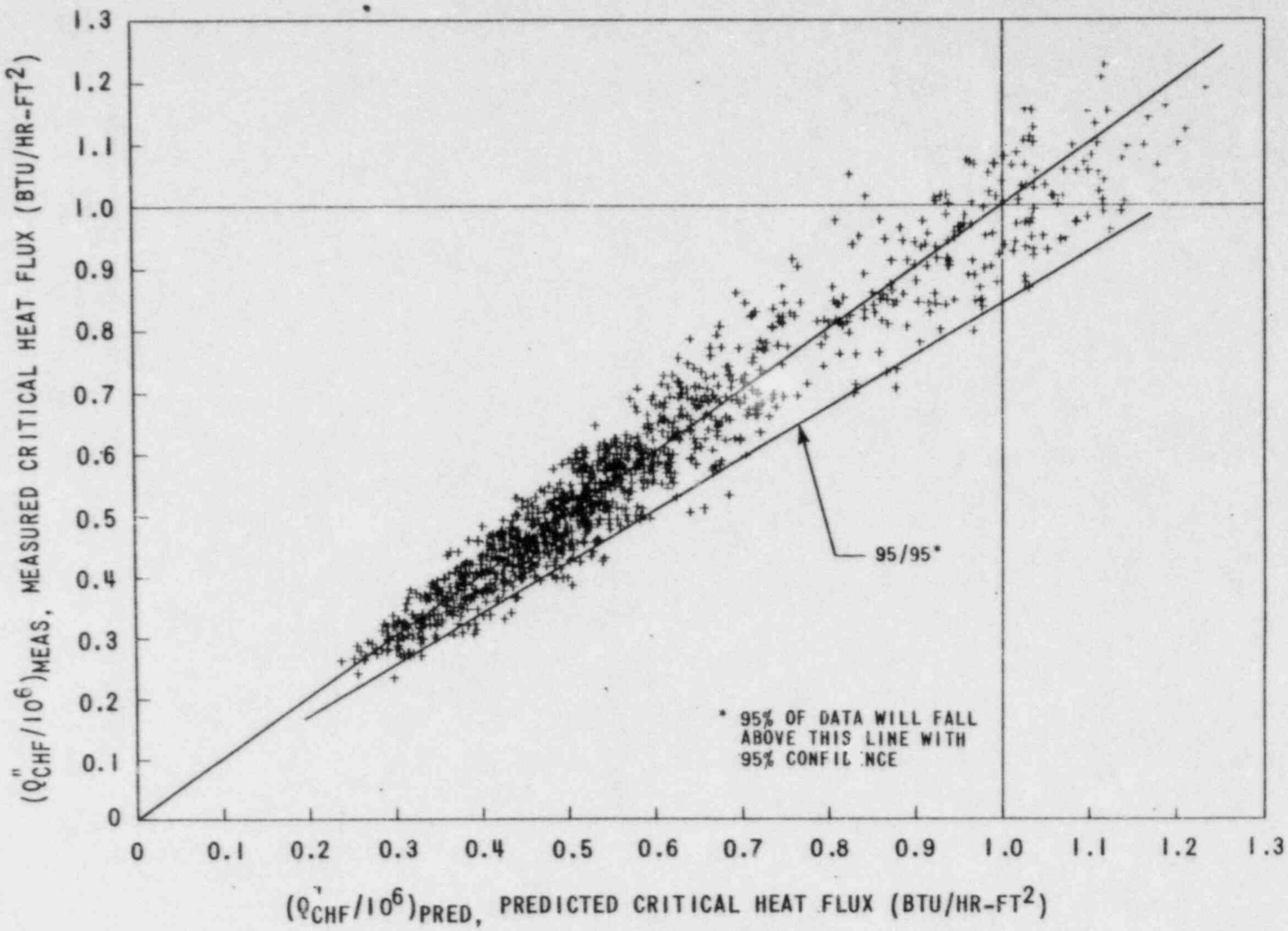


Figure 3-3. Measured versus Predicted Critical Heat Flux - WRB-1 Correlation

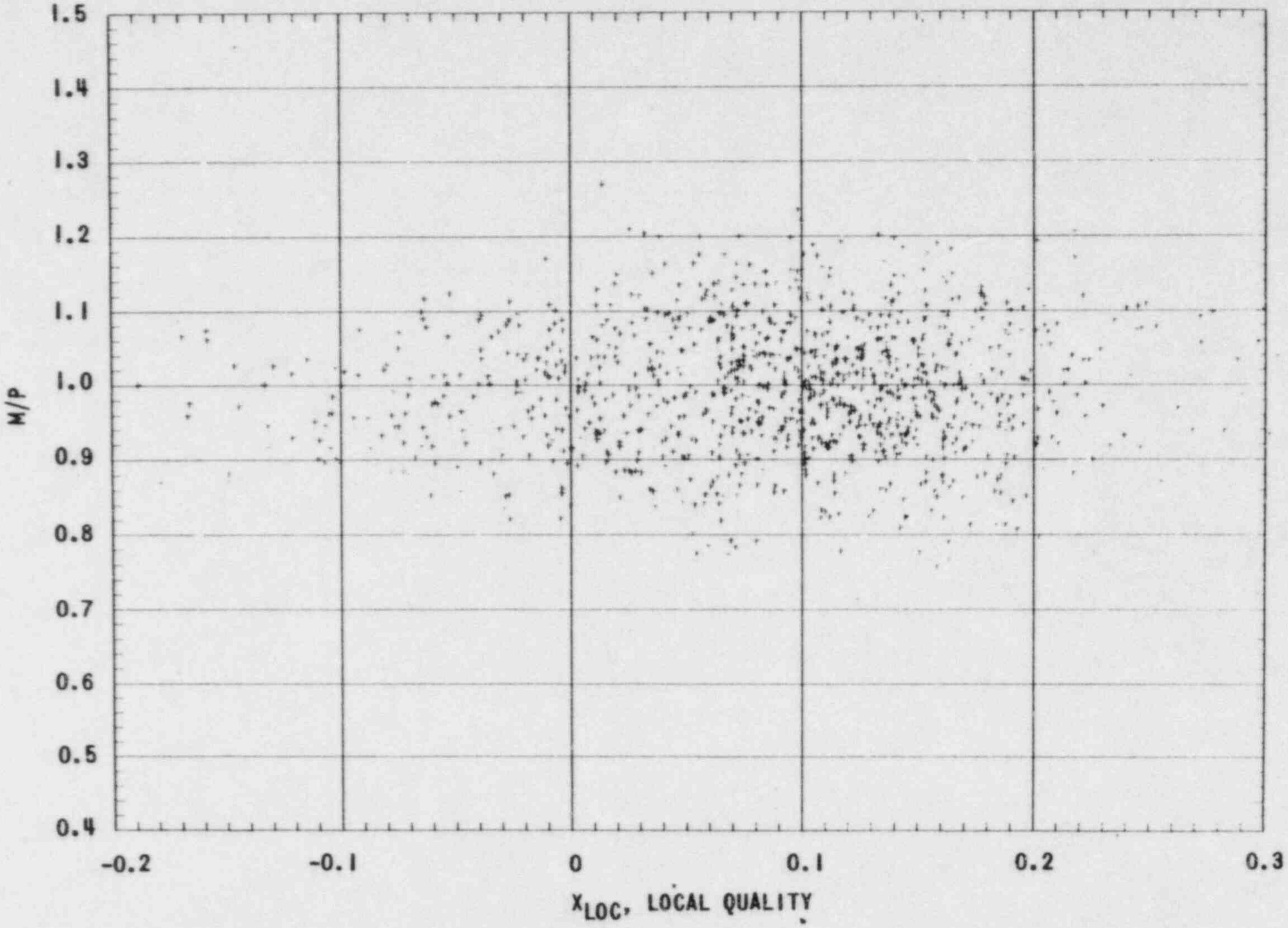


Figure 3-4. Measured-to-Predicted Critical Heat Flux versus Local Quality - WRB-1 Correlation

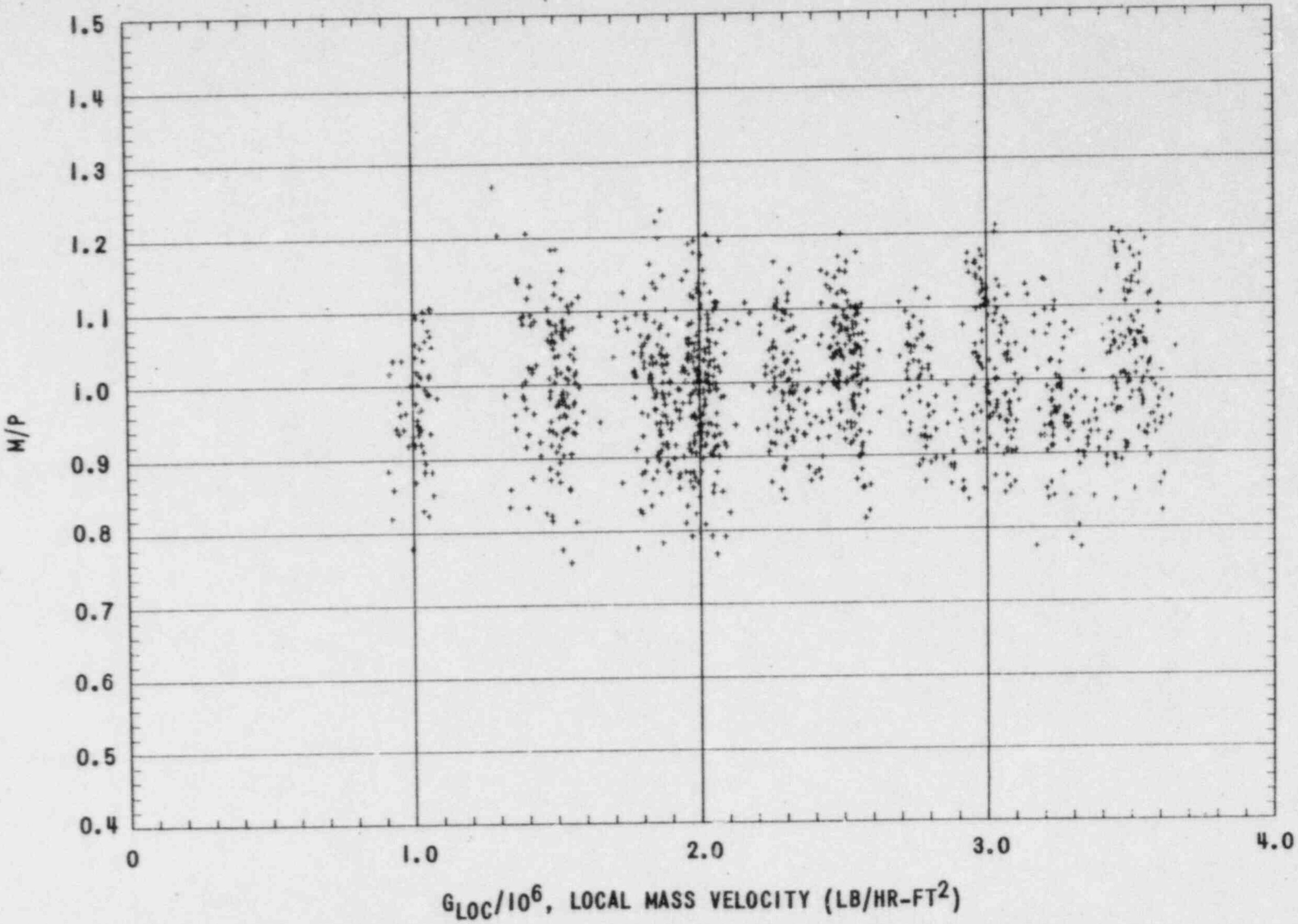


Figure 3-5. Measured-to-Predicted Critical Heat Flux versus Local Mass Velocity - WRB-1 Correlation

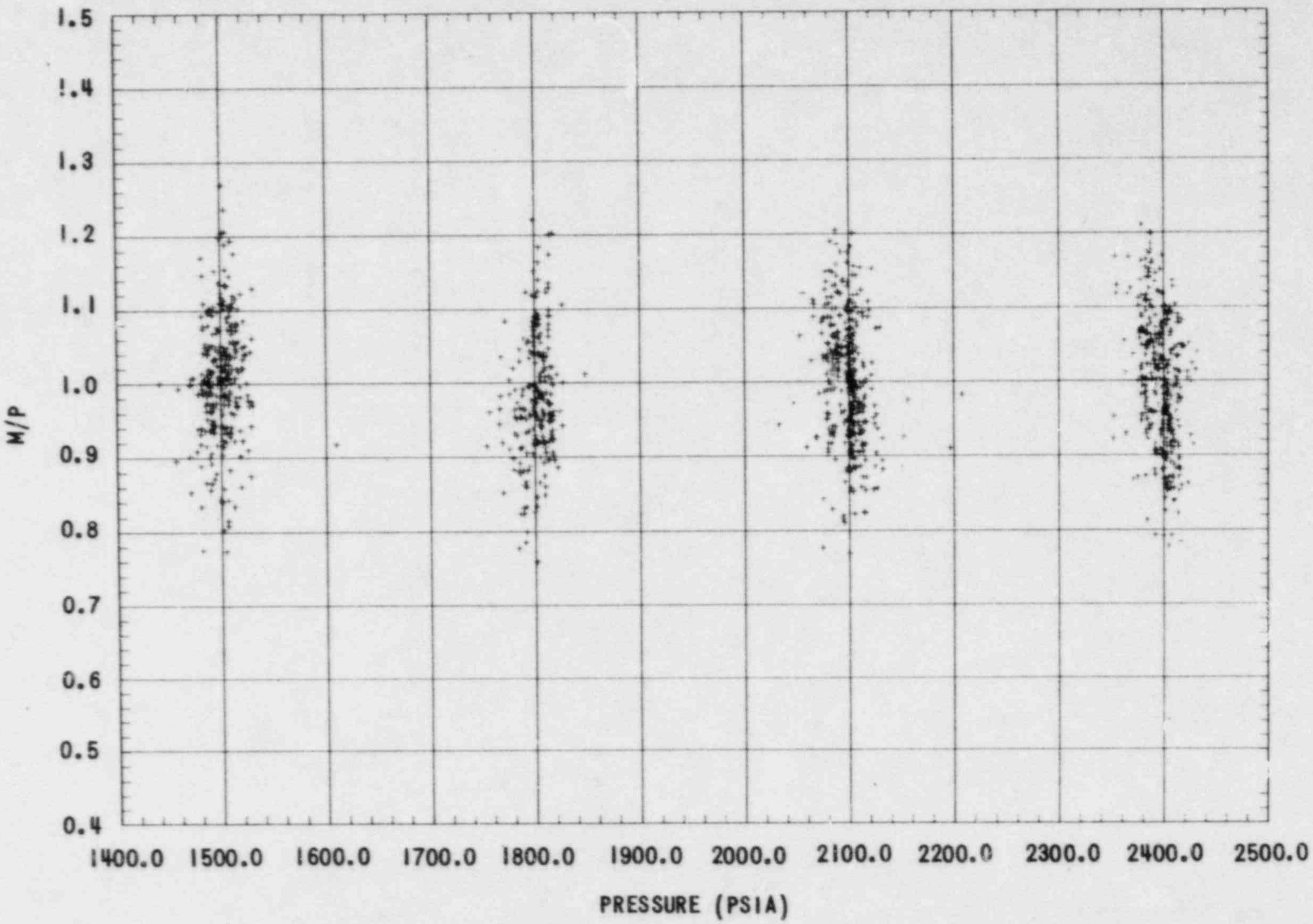


Figure 3-6. Measured-to-Predicted Critical Heat Flux versus Pressure - WRB-1 Correlation

SECTION 4
CONCLUSIONS

The *WRB-1* CHF correlation described in this report fits over 1100 rod bundle data points well, with no modification of the non-uniform F-factor. A significant improvement in the accuracy of CHF prediction has been obtained, with a minimum DNBR of 1.17 required to meet the reactor design criterion.

APPENDIX
WESTINGHOUSE ROD BUNDLE CHF DATA SUMMARY

TABLE A-1 TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1796							.8841		
W1797							.8160		
W1798							.9332		
W1799							.9946		
W1800							.9645		
W1801							1.0316		
W1802							1.1251		
W1803							.9387		
W1804							.9128		
W1805							.9507		
W1806							.9369		
W1807							.8887		
W1808							.9442		
W1809							.8914		
W1810							.9437		
W1811							.9322		
W1812							.9736		
W1813							.9527		
W1814							1.0119		
W1815							1.0602		
W1816							1.0560		
W1817							1.0324		
W1818							.9962		
W1819							1.0201		
W1820							1.0817		
W1821							1.0149		
W1822							.8948		
W1823							.9781		
W1824							.9730		
W1825							.9541		

(b,c)

L = 14 FT
DE = .4535 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-1 (cont) TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1826							1.0090		
W1827							1.0040		
W1828							1.0007		
W1829							.9224		
W1830							.9320		
W1831							1.0626		
W1832							1.0964		
W1833							.9744		
W1834							1.0192		
W1835							1.0704		
W1836							1.0374		
W1837							1.0562		
W1838							.9869		
W1839							1.1451		
W1840							1.0307		
W1841							.9985		
W1842							.9471		
W1843							1.0107		
W1844							.9635		
W1845							1.0032		
W1846							.9891		
W1847							1.0122		
W1848							1.0112		
W1849							1.0299		
W1850							.9839		
W1851							.9588		
W1852							.9826		
W1853							1.0503		
W1854							1.0477		
W1855							1.0200		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-1 (cont) TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1856							.9946		
W1857							1.0728		
W1858							1.1632		
W1859							.9737		
W1860							.9631		
W1861							1.0194		
W1862							1.1088		
W1863							1.0666		
W1864							1.0483		
W1865							.9450		
W1866							1.0351		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (F) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-2 TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (X)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1444							1.1532		
W1445							1.1093		
W1446							.9687		
W1447							1.0097		
W1448							.9306		
W1449							1.0262		
W1450							1.1031		
W1451							1.0990		
W1452							1.0410		
W1453							.9163		
W1454							.9335		
W1455							.9478		
W1456							.9811		
W1457							1.0493		
W1458							.9456		
W1459							.8598		
W1460							1.0316		
W1461							1.0030		
W1462							.9373		
W1463							.8559		
W1464							1.0740		
W1465							1.0734		
W1466							1.1832		
W1467							1.0030		
W1468							1.0008		
W1469							1.0834		
W1470							1.1016		
W1471							1.0807		
W1472							1.0034		
W1473							.9869		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (F) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-2 (cont) TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (X)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1474							.9818		
W1476							.8150		
W1477							1.1022		
W1478							1.0732		
W1479							1.0985		
W1480							1.0574		
W1481							1.1966		
W1482							.9330		
W1483							1.0418		
W1484							.8458		
W1486							.9002		
W1487							.9032		
W1488							.9865		
W1489							.9729		
W1490							.9194		
W1491							1.0218		
W1492							1.0050		
W1493							1.0376		
W1502							.9220		
W1503							.9720		
W1504							.9959		
W1505							1.0394		
W1506							1.0062		
W1507							1.0092		
W1508							.9690		
W1509							.9621		
W1525							.9425		
W1526							1.1173		
W1527							1.1192		
W1531							.8084		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-2 (cont) TEST RESULTS - 14 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1532							.9198		
W1534							1.0682		
W1535							1.1058		
W1540							1.0774		
W1541							1.0464		
W1543							1.0067		
W1544							1.0351		
W1545							.9434		
W1546							.9718		
W1552							1.0232		
W1553							.9246		
W1554							1.1012		
W1557							.9065		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-3 TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	MEAS/PRED	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1720							.9663		
W1721							1.0167		
W1722							1.0557		
W1723							1.1062		
W1724							.9413		
W1725							1.0489		
W1726							1.0825		
W1727							1.0931		
W1728							.9012		
W1729							1.0408		
W1730							1.0667		
W1731							1.1772		
W1732							.9163		
W1733							1.1293		
W1734							1.1544		
W1735							1.1934		
W1736							1.2171		
W1737							1.0525		
W1738							1.1052		
W1739							1.1041		
W1740							1.1197		
W1741							1.1942		
W1742							1.2192		
W1743							1.1494		
W1744							1.2068		
W1745							1.1696		
W1746							1.1575		
W1747							1.0946		
W1748							1.0939		
W1749							1.0725		

(b,c)

L = 8 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-3 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1750							1.1406		
W1751							1.1508		
W1752							1.0158		
W1753							.9820		
W1754							1.0554		
W1755							1.0684		
W1756							.9920		
W1757							.8609		
W1758							.9445		
W1759							.8564		
W1760							.9462		
W1761							.8303		
W1762							1.0119		
W1763							1.0124		
W1764							1.1372		
W1765							1.0097		
W1766							.7579		
W1767							.9047		
W1768							.9152		
W1769							.9893		
W1770							.9998		
W1771							.9344		
W1771*							1.1736		
W1772							1.1037		
W1773							1.1178		
W1774							1.0217		
W1775							1.1443		
W1776							1.0966		
W1777							1.2130		
W1778							1.1037		

(b,c)

L = 8 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-3 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1779							1.0082		
W1780							1.0833		
W1781							1.0320		
W1782							.9113		
W1783							.9435		
W1784							.9734		
W1785							1.0346		

(b,c)

L = 8 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-4 TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1559							1.0309		
W1560							.9432		
W1561							.9175		
W1562							.9447		
W1563							.8746		
W1564							.9115		
W1565							.9816		
W1566							.9377		
W1567							.8985		
W1568							.9941		
W1569							.9705		
W1570							1.0648		
W1571							.9143		
W1572							.9521		
W1573							.9620		
W1574							1.0700		
W1575							1.0290		
W1576							1.0097		
W1577							1.0359		
W1578							1.0708		
W1579							1.0449		
W1580							1.0057		
W1581							.9277		
W1582							.9938		
W1583							.8666		
W1584							1.0121		
W1585							1.0476		
W1586							.8309		
W1587							.8240		
W1589							.9814		

(b,c)

L = 8 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (9) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-4 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1589							.9003		
W1590							1.1037		
W1591							.7785		
W1592							.9431		
W1593							1.0252		
W1594							1.0533		
W1595							1.0363		
W1596							1.1053		
W1597							.9872		
W1598							1.0663		
W1599							1.0948		
W1600							1.1292		
W1601							1.0597		
W1602							.9795		
W1603							.9882		
W1604							1.1941		
W1605							1.0398		
W1606							1.0453		
W1607							1.0206		
W1608							1.0789		
W1609							1.0617		
W1610							1.0546		
W1611							.9764		
W1612							.9599		
W1613							1.0044		
W1614							1.0822		
W1615							.9509		
W1616							.9841		
W1617							1.0615		
W1618							1.0769		

(b,c)

L = 8 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-4 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1619							1.0088		
W1620							.9443		
W1621							1.0512		
W1623							1.0702		
W1624							1.1249		
W1625							1.1743		
W1626							1.2066		
W1627							1.0187		
W1628							1.1012		
W1629							1.0197		
W1630							1.1305		
W1631							1.0809		
W1632							.9276		
W1633							1.0331		
W1634							1.0713		
W1635							1.0975		
W1636							1.1053		
W1637							1.1101		

(b,c)

L = 8 FT
DE = .4615 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (F) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-5 (cont) TEST RESULTS - 14 FOOT .374 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1979							.9555		
W1980							.9441		
W1981							.9967		
W1982							.9088		
W1983							1.0449		
W1984							1.0474		
W1985							.8683		
W1986							.9151		
W1987							.9196		
W1988							1.0330		
W1989							1.0882		
W1990							.8245		
W1991							.8584		
W1992							.9519		
W1993							.9352		
W1994							.9521		
W1995							.7923		
W1996							.8689		
W1997							.8721		
W1998							.8589		
W1999							.9291		
W2000							1.0031		
W2001							1.0264		
W2002							.9466		
W2003							.9909		
W2004							.9577		
W2005							.9592		
W2006							1.0119		
W2007							.9703		
W2008							1.1099		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (F) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-5 (cont)   TEST RESULTS - 14 FOOT .374 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W2009							1.0822		
W2010							1.0489		
W2011							1.0584		
W2012							1.0731		
W2013							1.0539		
W2014							1.0332		
W2015							.9760		
W2016							1.0036		
W2017							1.0546		
W2018							1.0203		
W2019							1.0005		
W2020							.8955		
W2021							.8713		
W2022							.9060		
W2023							1.0492		
W2024							1.1220		
W2025							1.0774		
W2026							1.0470		
W2027							1.0134		
W2028							1.1229		
W2029							.9552		
W2030							1.1231		
W2031							1.2024		
W2032							1.0391		
W2033							1.1277		
W2034							.9474		
W2035							1.0520		
W2036							1.0692		
W2037							.9822		
W2038							.9688		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-5 (cont) TEST RESULTS - 14 FOOT .374 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W2039							.9205		
W2040							1.0574		
W2041							1.0612		
W2042							1.1042		
W2043							1.0027		
W2044							1.1772		
W2045							1.1015		
W2046							.9537		
W2047							1.0929		
W2048							1.0144		
W2049							1.1088		
W2050							.9308		
W2051							1.0567		
W2052							1.0610		

(b,c)

L = 14 FT
DE = .4635 IN
9 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-6 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-475							.9112		
W-476							.9434		
W-477							.9524		
W-478							.9934		
W-479							.9730		
W-480							1.0671		
W-481							.9919		
W-482							1.0491		
W-483							1.0763		
W-484							.9606		
W-485							1.0352		
W-486							.9401		
W-487							.9646		
W-488							1.0024		
W-489							.9854		
W-490							1.0067		
W-491							1.0187		
W-492							.9849		
W-493							.9756		
W-494							1.0663		
W-496							1.0265		
W-497							1.0834		
W-498							1.0840		
W-499							.9654		
W-500							1.0224		
W-501							1.0251		
W-502							.9437		
W-503							1.0426		
W-504							1.0499		
W-505							1.0088		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 92%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0870

TABLE A-6 (cont) TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-506							1.0457		
W-507							.9861		
W-509							.9872		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 92%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0870

TABLE A-7 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-510							.8407		
W-511							.9594		
W-512							.9706		
W-513							.9738		
W-514							.9292		
W-515							1.0561		
W-516							1.0617		
W-517							.8930		
W-518							.9941		
W-519							1.0128		
W-520							.9103		
W-521							.9754		
W-522							1.0140		
W-523							.8616		
W-524							.9787		
W-525							1.0273		
W-526							.9456		
W-527							.9306		
W-528							.9760		
W-529							.9677		
W-530							1.0061		
W-531							1.0139		
W-532							.9847		
W-533							1.0213		
W-534							1.0810		
W-535							.9606		
W-536							1.0354		
W-537							1.0754		
W-538							1.0121		
W-539							1.0506		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-7 (cont) TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-540									
W-541									
W-542									

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS

ROD O.D. = .422 IN
MIXING VANE GRIDS (9) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-8 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-550							.8834		
W-551							.9422		
W-552							.8921		
W-553							.9564		
W-554							.9063		
W-555							.9711		
W-556							.9630		
W-557							.9153		
W-558							.9459		
W-559							.9760		
W-560							.9116		
W-561							.9184		
W-562							.9268		
W-563							.8539		
W-564							.9223		
W-565							.9030		
W-566							.9231		
W-567							.9526		
W-568							.9595		
W-569							.8990		
W-570							.9425		
W-571							.9877		
W-572							1.0397		
W-573							1.1082		
W-574							1.1132		
W-575							1.0879		
W-576							1.1169		
W-577							1.0034		
W-578							1.0150		
W-579							1.0950		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2068

TABLE A-8 (cont) TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-580							1.0018		
W-581							.9641		
W-582							.9730		
W-583							1.0020		
W-585							1.2047		
W-586							1.2699		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-9 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-519							1.0894		
W-620							1.1149		
W-621							.9677		
W-622							1.1242		
W-623							1.0794		
W-624							1.1024		
W-625							1.1060		
W-626							1.1298		
W-627							1.1758		
W-628							1.0736		
W-629							1.1506		
W-630							1.0164		
W-631							1.0434		
W-632							.9565		
W-633							1.0358		
W-634							1.1163		
W-635							1.1360		
W-636							1.0954		
W-637							1.0846		
W-638							1.1762		
W-639							1.1102		
W-640							1.0533		
W-641							1.0841		
W-642							1.0199		
W-643							1.0258		
W-644							1.0070		
W-645							.9985		
W-646							.9850		
W-647							.8233		
W-648							1.0919		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (P) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-9 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.	
W-649							1.0543			(b,c)
W-650							1.0012			
W-651							.8802			
W-652							.9450			
W-653							1.1900			

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (8) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-10 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-654							1.1315		
W-655							1.0771		
W-656							.9940		
W-657							.9113		
W-658							1.0153		
W-659							.9967		
W-660							1.0556		
W-661							1.0533		
W-662							1.0621		
W-663							1.1174		
W-664							1.0966		
W-665							1.1014		
W-666							1.1476		
W-667							1.0600		
W-668							1.1191		
W-669							1.0669		
W-670							1.0483		
W-671							1.0007		
W-672							1.0514		
W-673							.7921		
W-674							1.0289		
W-675							1.0217		
W-676							1.0402		
W-677							.9602		
W-678							1.0353		
W-679							.9185		
W-680							.8099		
W-681							.8338		
W-682							.8594		
W-683							1.0338		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-10 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-684							1.1022		
W-685							.8663		
W-686							1.0314		
W-687							1.0007		
W-688							.9684		
W-689							.9505		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-11 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-690							1.1715		
W-691							.9494		
W-692							1.0810		
W-693							.9696		
W-694							1.0264		
W-695							.8726		
W-696							.8803		
W-697							.9876		
W-698							.9994		
W-699							.9580		
W-700							.8791		
W-701							.9217		
W-702							.9055		
W-703							.7990		
W-704							.9006		
W-705							1.0087		
W-706							.9515		
W-707							.9433		
W-708							1.0036		
W-709							1.0054		
W-710							1.0407		
W-711							.9853		
W-712							.9642		
W-713							.9560		
W-714							1.0373		
W-715							.9532		
W-716							1.0192		
W-717							1.1155		
W-718							.9354		
W-719							.9569		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 13 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-11 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-720							.9397		
W-721							1.0614		
W-722							1.0396		
W-723							.9067		
W-724							1.0779		
W-725							1.0674		
W-726							.8568		
W-727							.8715		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 13 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-12 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-728							.9822		
W-729							.9833		
W-730							1.1488		
W-731							1.1428		
W-732							1.0511		
W-733							1.1266		
W-734							1.0033		
W-735							1.0990		
W-736							1.1591		
W-737							1.1064		
W-738							1.0635		
W-739							1.1988		
W-740							.9862		
W-741							1.0367		
W-742							1.0777		
W-743							1.0189		
W-744							.9976		
W-745							.9648		
W-746							1.0375		
W-747							.9061		
W-748							1.0452		
W-749							1.0669		
W-750							.9844		
W-751							.8671		
W-752							1.0163		
W-753							1.0175		
W-754							1.0383		
W-755							1.0304		
W-756							1.0152		
W-757							1.0084		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-12 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-758							1.0335		
W-759							.9740		
W-760							.9116		
W-761							.9543		
W-762							.9521		
W-763							.9744		
W-764							.8778		
W-765							1.0482		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-13 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-878							.7755		
W-879							.9247		
W-880							.8618		
W-881							.9168		
W-882							.9279		
W-883							.9397		
W-884							.9990		
W-886							.9579		
W-887							1.1270		
W-888							.9346		
W-889							.9985		
W-890							.9538		
W-891							.9245		
W-892							1.0051		
W-893							.9869		
W-894							1.0370		
W-895							.9976		
W-896							.9880		
W-897							1.1099		
W-898							1.0077		
W-899							1.0422		
W-900							1.0966		
W-901							1.0672		
W-902							1.0116		
W-903							1.0551		
W-904							.9818		
W-905							1.0215		
W-906							1.0587		
W-907							1.0294		
W-908							.9761		

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-13 (cont) TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.	
W-909	[					]	1.0147	[	]	(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-14 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1177							1.0846		
W1178							1.1456		
W1179							1.1380		
W1180							1.0967		
W1181							1.1219		
W1182							1.1079		
W1183							1.0230		
W1184							1.0347		
W1185							1.0705		
W1186							1.1203		
W1187							1.1490		
W1188							1.0094		
W1189							1.3721		
W1190							1.0820		
W1191							1.1628		
W1192							1.1703		
W1193							.9418		
W1194							1.0021		
W1195							1.[illegible]234		
W1196							[illegible]0652		
W1197							[illegible]215		
W1198							.9481		
W1199							.9977		
W1200							1.0310		
W1201							1.0592		
W1202							1.0879		
W1203							1.0615		
W1204							1.1304		
W1205							1.0447		
W1206							1.1650		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (8) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-14 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1207							1.1531		
W1208							1.1363		
W1209							.9942		
W1210							1.0043		
W1211							1.0700		
W1212							1.1049		
W1213							1.0966		
W1214							1.0496		
W1215							.9986		
W1216							1.2002		
W1217							1.1132		
W1218							1.2110		
W1219							1.1207		
W1220							1.0100		
W1221							1.0431		
W1222							1.0138		
W1223							1.0744		
W1224							1.0522		
W1225							1.0395		
W1226							1.0141		
W1227							.9840		
W1228							.9242		
W1229							.9325		
W1230							.9642		
W1232							.8133		
W1233							.7759		
W1234							.9479		
W1235							1.0024		
W1236							1.0232		
W1237							.9270		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-14 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1238							.9909		
W1239							1.0094		
W1240							.9871		
W1241							1.0120		
W1242							.9391		
W1243							.9408		
W1244							.9737		
W1245							1.0681		
W1246							1.1624		
W1247							1.1084		
W1249							1.0463		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-15 TEST RESULTS - 14 FOOT .422 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1391							1.0075		
W1392							.9208		
W1393							.8652		
W1394							.8483		
W1395							.9501		
W1397							.9659		
W1398							.7682		
W1399							.9296		
W1400							1.0023		
W1401							.8518		
W1402							.9269		
W1403							.9816		
W1404							.9586		
W1405							1.0145		
W1406							.9161		
W1407							.9494		
W1408							.9888		
W1409							1.0020		
W1410							.9458		
W1411							1.0181		
W1412							.9731		
W1413							.9058		
W1414							.9351		
W1415							.9912		
W1416							.9046		
W1417							.9367		
W1418							.9499		
W1419							.9328		
W1420							.8867		
W1421							.9040		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-15 (cont) TEST RESULTS - 14 FOOT .422 INCH OD UNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1422							.8258		
W1423							.9178		
W1424							.9148		
W1425							.8805		
W1426							.8217		
W1427							.9613		
W1428							1.0043		
W1429							.9823		
W1430							.9912		
W1431							.9446		
W1432							.9372		
W1433							.9334		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-16 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1097							.9533		
W1098							1.0276		
W1099							.9769		
W1100							.9743		
W1101							.9386		
W1102							1.0520		
W1103							1.0053		
W1104							1.0452		
W1105							.9729		
W1106							1.0914		
W1107							1.0283		
W1108							1.0932		
W1109							.9775		
W1110							1.0226		
W1111							1.0549		
W1112							1.0332		
W1113							.9305		
W1114							.9592		
W1115							1.1163		
W1116							.9491		
W1117							1.0565		
W1118							1.1209		
W1119							.9297		
W1120							1.0535		
W1121							1.0931		
W1122							1.1246		
W1123							1.0857		
W1124							.9895		
W1125							1.0096		
W1126							1.0156		

(b,c)

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-16 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1127							.9069		
W1128							.9894		
W1129							1.0574		
W1130							.9948		
W1131							.9436		
W1132							.9595		
W1133							.9724		
W1134							1.0167		
W1135							1.0294		

(b,c)

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-17 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-840							.8348		
W-841							.9350		
W-842							.8685		
W-843							.9327		
W-844							.9925		
W-845							.8839		
W-846							.9563		
W-847							1.0393		
W-848							1.0185		
W-849							1.0862		
W-850							.8886		
W-851							.9214		
W-852							.9483		
W-853							.9926		
W-854							.8245		
W-855							.9121		
W-856							1.0095		
W-857							1.0472		
W-858							1.0549		
W-859							.9799		
W-860							.7870		
W-861							.9389		
W-862							.9378		
W-863							.9337		
W-864							1.0149		
W-865							1.1151		
W-866							.8291		
W-867							.9295		
W-868							1.0217		
W-869							1.0775		

(b,c)

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-17 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-870							1.0464		
W-871							1.0644		
W-872							1.0880		
W-873							.9258		
W-874							1.1342		
W-875							1.1053		
W-876							.9168		

(b,c)

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (R) 32 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-18 TEST RESULTS - 14 FOOT .374 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1857							1.0124		
W1869							1.0652		
W1859							1.0701		
W1870							1.0305		
W1871							.9856		
W1872							.9909		
W1873							1.0492		
W1874							.9553		
W1875							.8943		
W1876							.8543		
W1877							.9574		
W1878							1.0828		
W1879							.9471		
W1880							.8547		
W1881							1.0072		
W1882							.9943		
W1883							1.0614		
W1884							1.0948		
W1885							.9909		
W1886							1.1506		
W1887							1.0374		
W1888							.9474		
W1889							1.1773		
W1890							1.0488		
W1891							.9277		
W1892							.9485		
W1893							1.0576		
W1894							1.0156		
W1895							.9935		
W1896							.9510		

(b,c)

L = 14 FT
DE = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-18 (cont) TEST RESULTS - 14 FOOT .374 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1897							1.0187		
W1898							.9718		
W1899							.8875		
W1900							1.0722		
W1901							.9236		
W1902							.9246		
W1903							311		
W1904							1.0208		
W1905							1.0165		
W1906							.8614		
W1907							.9041		
W1908							.9047		
W1909							1.0250		
W1910							.8752		
W1911							1.1195		
W1912							.9186		
W1913							.9492		
W1914							1.0954		
W1915							.9789		
W1916							.9438		
W1917							.9739		
W1918							.8975		
W1919							.9405		
W1920							1.0101		
W1921							.9376		
W1922							1.1342		
W1923							1.0338		
W1924							1.0538		
W1925							1.0015		
W1926							.9637		

(b,c)

L = 14 FT
DE = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-18 (cont) TEST RESULTS - 14 FOOT - .374 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1927							.9551		
W1928							1.0946		
W1929							1.0372		
W1930							1.1355		
W1931							.9892		
W1932							1.0806		
W1933							1.1037		
W1934							1.1017		
W1935							1.0368		
W1936							1.1502		

(b,c)

L = 14 FT
DE = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 22 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-19 TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1638							1.0572		
W1639							1.0034		
W1640							1.0390		
W1641							1.1091		
W1642							1.0520		
W1643							1.0242		
W1644							1.0343		
W1645							1.0511		
W1646							.7829		
W1647							.8428		
W1648							.9432		
W1649							.9461		
W1650							.8812		
W1651							.9131		
W1652							1.0570		
W1653							.9520		
W1654							1.1079		
W1655							1.0423		
W1656							1.1792		
W1657							1.1150		
W1658							1.0408		
W1659							1.0590		
W1660							1.0165		
W1661							.9438		
W1662							.8189		
W1663							.8958		
W1664							1.1611		
W1665							1.1481		
W1666							1.1136		
W1667							.9943		

(b,c)

L = 8 FT
DE = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (R) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1 65

TABLE A-19 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1668							.9671		
W1669							.8470		
W1670							.9437		
W1671							.9279		
W1672							.9821		
W1673							1.0716		
W1674							.9759		
W1675							.9539		
W1676							.9563		
W1677							.9445		
W1678							.9238		
W1679							.9232		
W1680							1.0569		
W1681							1.1036		
W1682							1.1079		
W1683							1.0939		
W1684							1.0911		
W1685							1.0390		
W1686							1.0440		
W1687							1.0432		
W1688							1.0599		
W1689							.9731		
W1690							1.1056		
W1691							1.2392		
W1692							1.1775		
W1693							1.2518		
W1694							1.2172		
W1695							1.1692		
W1696							1.0293		
W1697							1.0971		

(b,c)

L = 8 FT
DE = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (8) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-19 (cont) TEST RESULTS - 8 FOOT .374 INCH OD UNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1698							.9586		
W1699							.8670		
W1700							.9523		
W1701							1.1576		
W1702							1.0604		
W1703							1.1518		
W1704							1.2537		
W1705							1.0199		

(b,c)

L = 8 FT
DH = .3713 IN
8 RODS 100%
16 RODS 85%

ROD O.D. = .374 IN
MIXING VANE GRIDS (F) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-20 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-217	1500.0	516.7	2.548				.8658		75.0
W-218	1500.0	496.7	2.560				.9065		75.0
W-219	1500.0	481.0	2.546				.9402		81.0
W-220	1530.0	559.7	3.596				.7732		57.0
W-221	1530.0	539.3	3.590				.8438		57.0
W-222	1815.0	580.7	3.543				.7847		57.0
W-223	1810.0	560.0	3.677				.8912		57.0
W-224	2115.0	583.0	2.561				.8772		75.0, 63.0, 57.0
W-225	2115.0	565.3	2.553				.8960		57.0
W-226	2113.1	546.0	2.572				.8857		75.0
W-227	2119.7	599.0	3.097				.8512		57.0
W-228	2128.8	583.7	3.058				.9045		57.0, 75.0
W-229	2137.7	559.3	3.104				.8858		75.0
W-230	2100.0	600.3	3.573				.8423		57.0
W-231	2120.0	585.3	3.584				.9452		75.0
W-232	2110.0	566.3	3.565				.9396		75.0
W-233	2420.0	626.3	3.538				.9059		63.0, 57.0,
W-234	2420.0	602.5	3.611				.8949		75.0
W-235	2410.0	583.7	3.589				.9017		75.0
W-236	2430.0	624.3	3.027				.8867		75.0
W-237	2420.0	602.2	3.064				.8907		75.0
W-238	2427.5	580.3	3.089				.8957		75.0
W-239	2410.0	579.3	2.576				.8671		75.0
W-240	2410.0	553.7	2.566				.8814		75.0
W-241	2385.0	537.0	2.562				.8704		75.0
W-242	2410.0	558.3	2.090				.8580		75.0
W-243	2390.0	541.0	2.059				.8727		75.0
W-244	2418.8	514.3	2.068				.8807		75.0
W-245	2119.5	537.7	2.035				.9185		75.0
W-246	2109.5	515.3	2.064				.9135		75.0

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 94%

ROD O.D. = .422 IN
MIXING VANE GRIDS (L) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0638

(b,c)

TABLE A-20 (cont) TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-247	2109.4	499.7	2.052				.9162		75.0
W-248	1800.1	499.7	2.109				.8808		91.0
W-249	1819.6	477.7	2.019				.8960		91.0
W-250	1517.4	470.3	1.549				.8345		75.0
W-251	1507.4	452.0	1.546				.8592		75.0
W-252	1507.0	415.3	1.563				.9156		91.0, 75.0

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 94%

ROD O.D. = .422 IN
MIXING VANE GRIDS (I) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0638

TABLE A-21 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1056							1.0514		
W1057							1.0067		
W1058							.9946		
W1059							.9733		
W1060							1.0796		
W1061							1.0014		
W1062							1.0580		
W1063							1.0341		
W1064							1.2050		
W1065							1.1850		
W1066							1.1848		
W1067							1.1763		
W1068							1.1010		
W1069							1.1510		
W1070							1.1725		
W1071							1.1248		
W1072							1.1409		
W1073							1.1463		
W1074							1.0524		
W1075							1.1201		
W1076							1.1401		
W1077							1.0306		
W1078							1.1434		
W1079							1.1594		
W1080							1.0595		
W1081							1.1307		
W1082							1.1510		
W1083							.9916		
W1084							1.0798		
W1085							1.0894		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (I) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-21 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1086							.9133		
W1097							.9289		
W1088							.9539		
W1089							1.0429		
W1090							1.0482		
W1091							1.0503		
W1092							1.05[illegible]4		
W1093							1.0411		
W1094							1.0192		
W1095							1.0169		
W1096							1.0439		

(b,c)

L = 14 FT
DE = .5074 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (L) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

Table A-22 TEST RESULTS - 8 FOOT .422 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-8	1500.0	520.0	2.501				.9872		69.0
W-9	1500.0	499.0	2.503				1.0465		69.0
W-10	2166.3	594.0	2.587				.9260		69.0
W-11	2115.1	567.0	2.551				.9901		69.0
W-12	2415.6	577.0	2.541				.9564		69.0
W-13	2410.8	559.0	2.062				.9629		69.0
W-14	1500.0	560.0	3.427				.8535		69.0
W-15	1800.0	579.0	3.550				.9199		69.0
W-16	1819.9	500.0	1.910				1.0365		69.0
W-17	1500.0	545.0	3.602				.9021		69.0
W-18	1500.0	482.0	2.479				1.0952		69.0
W-19	1530.0	466.0	1.972				1.0852		90.0, 81.0
W-53	1532.0	558.0	3.575				.8025		69.0
W-54	1842.0	560.0	3.617				.8969		69.0
W-55	1790.0	481.5	2.033				.9911		69.0
W-56	2112.0	502.5	2.025				.9465		69.0
W-57	2118.0	517.5	2.039				.9466		69.0
W-58	2120.0	541.5	2.029				.9312		69.0
W-59	2128.0	545.0	2.529				.9453		69.0
W-60	2135.0	567.5	3.062				.9586		69.0, 81.0, 90.0
W-61	2150.0	581.0	3.072				.8813		69.0
W-62	2120.0	601.5	3.044				.8646		69.0
W-63	2130.0	566.0	3.578				1.0113		75.0, 81.0
W-64	2135.0	594.0	3.460				.8854		69.0
W-65	2110.0	577.5	3.572				.9291		69.0
W-66	2410.0	580.0	3.095				.9156		75.0, 81.0, 90.0, 84.0
W-67	2425.0	602.0	3.072				.8536		75.0, 90.0
W-68	2430.0	623.0	3.050				.8398		69.0
W-69	2440.0	627.0	3.561				.8380		69.0, 81.0, 90.0

(b,c)

L = 8 FT
DE = .5074 IN
4 RODS 100%
12 RODS 83%

ROD O.D. = .422 IN
MIXING VANE GRIDS (L) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.2048

TABLE A-23 TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W1018							.8443		
W1019							.9866		
W1020							.9568		
W1021							.9852		
W1022							.9504		
W1023							.8950		
W1024							1.0747		
W1025							1.1124		
W1026							1.1253		
W1027							.9962		
W1028							1.0416		
W1029							1.1356		
W1030							1.0565		
W1031							1.1099		
W1032							.9926		
W1033							1.0462		
W1034							1.0640		
W1035							.9182		
W1036							.9885		
W1037							1.0355		
W1038							.9948		
W1039							1.0054		
W1040							1.1069		
W1041							1.0434		
W1042							.9391		
W1043							.9634		
W1044							.9655		
W1045							1.0927		
W1046							1.0489		
W1047							.9723		

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (I) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

(b,c)

TABLE A-23 (cont) TEST RESULTS - 14 FOOT .422 INCH OD NONUNIFORM TEST SECTION
COLD WALL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W1048							1.0021		
W1049							.8983		
W1050							.9022		
W1051							.9586		
W1052							.8895		
W1053							.9197		
W1054							.9725		
W1055							1.0030		

(b,c)

L = 14 FT
DE = .4080 IN
3 RODS 100%
12 RODS 85%

ROD O.D. = .422 IN
MIXING VANE GRIDS (I) 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE A-24 TEST RESULTS - 14 FOOT .500 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	(MEAS/PRED)	ELEVATION FROM INLET (INCHES) PRED.	MEAS.
W-20	1532.4	495.0	2.553				.9416		141.1
W-21	1541.0	483.0	2.559				.9494		141.1
W-22	1840.4	519.0	2.511				.9473		141.1
W-23	1870.2	501.0	2.488				.9639		141.1
W-24	2121.9	564.0	2.530				.9519		141.1
W-25	2121.3	544.0	2.547				1.0144		141.1
W-26	2421.3	581.0	2.562				.9961		141.1
W-27	2420.4	564.0	2.544				1.0069		141.1
W-28	2419.9	543.0	2.559				1.0111		141.1
W-29	2400.0	620.0	3.426				1.0537		141.1, 121.0
W-30	2400.0	601.0	3.577				1.1073		141.1, 121.0
W-31	2400.0	605.0	3.007				1.0516		141.1
W-32	2400.0	582.0	3.028				1.1062		121.0
W-33	2414.9	560.5	2.005				.9959		141.1
W-34	2414.7	543.0	2.036				1.0177		141.1
W-35	2414.3	520.0	2.035				1.0129		141.1
W-36	2100.0	596.0	3.560				1.0043		141.1
W-37	2100.0	579.0	3.530				1.0623		141.1
W-38	2100.0	602.0	2.996				.9683		141.1
W-39	2100.0	577.0	3.048				1.0280		141.1
W-40	2100.0	561.0	3.060				1.0485		141.1
W-41	2115.8	544.0	2.001				.9945		141.1
W-42	2115.3	518.0	2.030				.9871		141.1
W-43	2115.1	501.0	2.037				.9932		141.1
W-44	1800.0	580.0	3.516				.9675		141.1
W-45	1800.0	563.0	3.507				.9133		141.1
W-46	1800.0	559.0	3.014				.9144		141.1
W-47	1800.0	540.0	3.019				.9339		141.1
W-48	2100.0	524.0	2.501				1.0475		141.1
W-49	1816.6	494.0	2.057				1.0115		141.1

(b,c)

L = 14 FT
DE = .6025 IN
9 RODS 100%

ROD O.D. = .500 IN
MIXING VANE GRIDS (I) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0000

TABLE A-24 (cont) TEST RESULTS - 14 FOOT .500 INCH OD NONUNIFORM TEST SECTION
TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) PRED.	(MEAS/ PRED)	ELEVATION FROM INLET (INCHES) PRED.	ELEVATION FROM INLET (INCHES) MEAS.
W-50	1500.0	541.0	3.471				.8535		141.1
W-51	1500.0	514.0	3.525				.9499		141.1 (b,c)
W-52	1815.8	482.0	2.035				1.0250		141.1

L = 14 FT
DE = .6025 IN
9 RODS 100%

ROD O.D. = .500 IN
MIXING VANE GRIDS (L) 20 IN SPACING
INNER ROD/OUTER ROD POWER = 1.0000

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 2 8 1977

Mr. C. Eicheldinger, Manager
Nuclear Safety Department
Westinghouse Electric Corporation
P. O. Box 355
Pittsburgh, Pennsylvania 15230

Dear Mr. Eicheldinger:

SUBJECT: STAFF REVIEW OF WCAP-8762

Additional information is needed to complete our review of Westinghouse Electric Corporation report WCAP-8762 (Proprietary) entitled "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids". The required additional information is described in the enclosure.

Your response to these requests is needed by October 25, 1977 in order to complete our review as scheduled. If you cannot meet this schedule, please advise us within ten days after receipt of this letter so that we may revise our schedule.

If you have any questions about our request for additional information, please contact us.

Sincerely,

John F. Stolz

John F. Stolz, Chief
Light Water Reactors Branch No. 1
Division of Project Management

Enclosure:
Request for Additional Information

ENCLOSURE

REQUEST FOR ADDITIONAL INFORMATION ON WCAP-8762

1. Provide a complete description of how the local conditions for the WRB-1 correlation were calculated in developing the correlation. The description should include a discussion of: the subchannel code used; subchannel modeling; axial nodalization; and input assumptions (such as Thermal Diffusion Coefficient, friction factors, spacer grid loss coefficient, treatment of mixing grids and non-mixing grids).

2. The inclusion of the d_g term (distance from the last mixing vane grid) makes the WRB-1 correlation a stronger function of axial position than previous correlations. Provide a description of how the axial locations at which the correlation is evaluated are chosen for the CHF tests; that is, how the thermocouple locations are chosen and how the locations at which the correlation is evaluated will be chosen in the application of the correlation to reactor design and safety calculations.

3. What value of the performance factor (PF) is used for the 0.5 inch O.D. Rods in the 3x3 CHF tests?

4. Provide the correct value of the coefficient for the pressure squared term (B45) on page 2-5.

5. The Westinghouse topical report "Effects of Local Heat Flux Spikes on DNB in Non-Uniformly Heated Rod Bundles" (WCAP-8174-PA, Feb., 1975) adequately demonstrates that a special DNB heat flux spike factor need not be incorporated into the Westinghouse reactor design using Westinghouse type mixing vane grids when the W-3 CHF correlation is used. Provide a similar analysis to justify not including a special DNB heat flux spike when the WRB-1 correlation is used for reactor design.

6. To date the information presented to the staff on the effects of rod bowing on DNB has been based on a combination of CHF tests and calculation using the W-3 CHF correlation. Justify the use of this information with the WRB-1 correlation or provide information on changes in CHF and the equivalent change in $F^N_{\Delta H}$ when the WRB-1 correlation is applied.

7. Section 4 of WCAP-8762 proposes the use of a 1.17 Minimum DNBR for reactor design calculation. This value is based on 95% probability of not experiencing DNB at a 95% confidence level when all of the data are considered (i.e., 1147 data points). Since each reactor design contains only one heated length; one fuel rod size; one type of mixing vane grid, etc., the use of CHF data from CHF test on other geometries (i.e., other heated lengths, fuel rod sizes, etc.) must be justified. This justification must be based on the fact that the correlation, in combination with the subchannel code, correctly treats the physical phenomena associated with the particular geometry change. For example, the treatment of different mixing grids is accomplished by using the appropriate loss coefficients in the subchannel calculation.

No empirical constants are required in the CHF correlation in order to fit the data. Therefore the data from the "R" grid and "L" grid CHF tests can be combined when computing the mean and standard deviation of the data and in establishing the correlation limit. However, the inclusion of the "Performance Factor" (a different value for the 5x5 type fuel and the 4x4 type fuel) in the WRB-1 correlation appears to be purely empirical. The requirement for a "Performance Factor" indicates that the CHF correlation and subchannel code are not representing all of the physical phenomena associated with the hydraulic diameter, rod size, pitch, change in mixing grid geometry, etc. Provide justification for the use of both the 5x5 and 4x4 test data in establishing the correlation limit.

If combination of the 5x5 type CHF data and the 4x4 type CHF data is not adequately justified, then the DNB limits must be established independently for 5x5 type fuel and 4x4 type fuel.

8. The form of the WRB-1 correlation includes a "Performance Factor" which is required to make the correlation fit both the 5x5 CHF data and the 4x4 data. The correlation indicates that the "Performance Factor" should be chosen based on the fuel rod outer diameter. This implies that the 5x5 "Performance Factor" also applies to 17x17 fuel since 17x17 fuel and the 5x5 test assembly both have rod diameters of 0.374 in. Similarly, the 4x4 "Performance Factor" would apply to 15x15 fuel. The 5x5 tests and the 4x4 tests differ in many areas, such as: rod diameter; pitch; equivalent diameter; equivalent heated diameter; mixing grid details; proximity of the CHF location to low power rods; proximity of the CHF location to the unheated walls; and proximity of the CHF location to the corner mixing vanes. A bias in CHF prediction or the subchannel conditions associated with one of these parameters could cause the difference in the 5x5 and 4x4 results. In order to apply the 5x5 and 4x4 data to 17x17 and 15x15 fuel assemblies, it is necessary to identify which of the differences between the 5x5 and the 4x4 tests causes the difference in the results (i.e., causes the need for the different "Performance Factors"). Therefore, provide a detailed discussion, including supporting calculations and test results, to justify the assumption that difference between the 5x5 and the 4x4 results is associated with difference in the rod diameter.

9. For test series A-3, WCAP-8762 indicates that for some cases the CHF location was measured at 84 inches from the test section inlet. WCAP-8536 which is referenced as the source of the information for test series A-3 shows the thermocouple location to be 85 inches from the inlet. Correct this discrepancy.

10. Provide the grid locations and thermocouple locations for the test series A-10. This information is not presently available because these tests were not previously published.

11. The staff has been unable to verify the results of the A-10 test series. We believe that this is because the USINU power distribution presented in WCAP-8762 and in the referenced reports does not have sufficient detail to allow an accurate representation in the COBRA IV code. Provide a more detailed graphical or numerical representation of the power distribution for test series A-10.

Westinghouse Electric Corporation Power Systems

Box 355
Pittsburgh Pennsylvania 15230

October 24, 1977

NS-CE-1581

Mr. John F. Stolz, Chief
Light Water Reactors Branch No. 1
Division of Projects Management
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Reference: 1. Letter from J. F. Stolz to C. Eicheldinger, September 28, 1977. Subject: Request for additional information on WCAP-8762 (P) and WCAP-8763 (NP).

Dear Mr. Stolz:

Enclosed are:

1. Twenty-five (25) copies of additional information on WCAP-8762 (Proprietary) as requested by Reference 1.

2. Twenty (20) copies of additional information on WCAP-8763 (Non-Proprietary).

Both reports are entitled, "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux In Rod Bundles With Mixing Vane Grids".

The information transmitted in this response is additional information to supplement Reference 1.

This submittal contains proprietary information. In conformance with the requirements of 10CFR 2.790, as amended, of the Commission's regulations, we are enclosing with this submittal, an application for withholding from public disclosure and an affidavit. The affidavit identifies the information sought to be withheld and sets forth the basis on which the information may be withheld from public disclosure by the Commission.

We expect that the non-proprietary version of this report, WCAP-8763, will be placed in the Public Document Room and identified as a Westinghouse Topical Report.

Correspondance with respect to the Westinghouse affidavit or application for withholding should be addressed to: R. A. Wiesemann, Manager, Licensing Programs, Westinghouse Electric Corporation, P. O. Box 355, Pittsburgh, Pennsylvania 15230.

Very truly yours,

C. Eicheldinger

C. Eicheldinger, Manager
Nuclear Safety Department

AP:pj
Enclosure

B.2

1. Provide a complete description of how the local conditions for the WRB-1 correlation were calculated in developing the correlation. The description should include a discussion of: the subchannel code used; subchannel modeling; axial nodalization: and input assumptions (such as Thermal Diffusion Coefficient, friction factors, spacer grid loss.

<u>Answer</u>

As in design, the THINC sub-channel code is used for the data reduction. The subchannel modeling is shown in the attached figure 1. The length of the axial nodes and other input variables are given in the attached table 1. The friction factors are calculated by the methods presented in Reference (2).

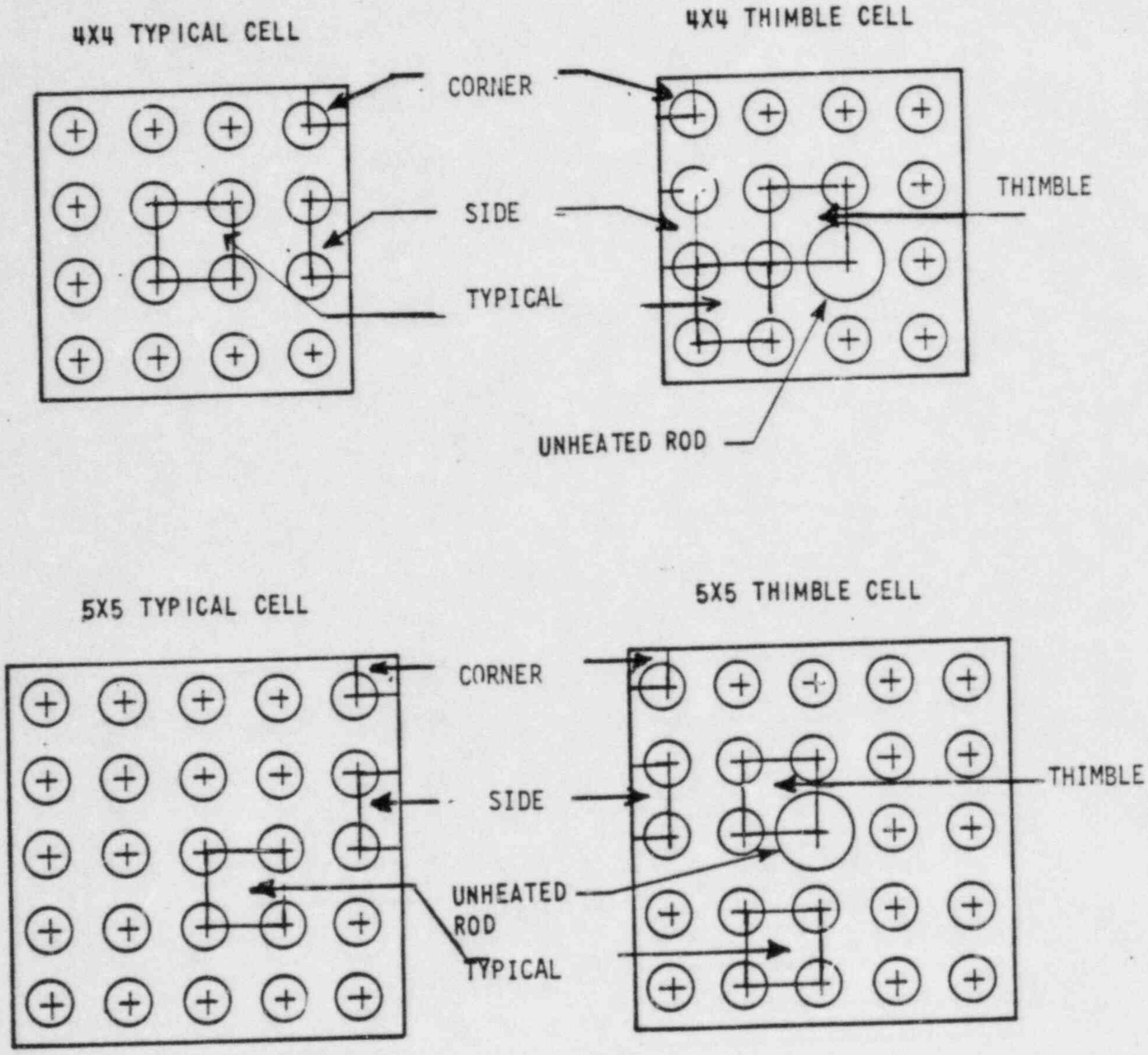


Figure 1 Cross-Sections of CHF Test Sections

TABLE 1. WRB-1 CHF CORRELATION - THINC ANALYSIS INPUTS

	Rod O.D. Inch	L_H ft	g_{sp} Inch	Heat Flux Profile	Configuration *	Table Ref (1)	Axial Node Length in.	TDC	Grid Loss Coef. - MV Grid				Grid Loss Coef. - Non-MV Grid				Vane Design	Performance Factor
									Corner	Side	Typ. Cell	Thim. Cell	Corner	Side	Typ. Cell	Thim. Cell		
"R" Grid	0.374	14	22	UNIF	TYP-5X5	A- 1	3.36									+	B	+
	0.374	14	26	UNIF	TYP-5X5	A- 2	3.36										B	
	0.374	8	22	UNIF	TYP-5X5	A- 3	2										B	
	0.374	8	26	UNIF	TYP-5X5	A- 4	2										B	
	0.374	14	22	COSINE	TYP-5X5	A- 5	3.36										B	
	0.422	8	20	COSINE	TYP-4X4	A- 6	3										A	
	0.422	8	20	USINU	TYP-4X4	A- 7	3										A	
	0.422	8	26	USINU	TYP-4X4	A- 8	3										A	
	0.422	14	26	USINU	TYP-4X4	A- 9	3.36										A	
	0.422	14	20	USINU	TYP-4X4	A-10	3.36										A	
	0.422	14	13	USINU	TYP-4X4	A-11	3.36										A	
	0.422	14	32	USINU	TYP-4X4	A-12	3.36										A	
	0.422	8	32	USINU	TYP-4X4	A-13	3										A	
	0.422	14	26	USINU	TYP-4X4	A-14	3.36										A	
	0.422	14	26	UNIF	TYP-4X4	A-15	3.36										A	
	0.422	14	26	USINU	TH -4X4	A-16	3.36										A	
	0.422	14	32	USINU	TH -4X4	A-17	3.36										A	
	0.374	14	22	COSINE	TH -5X5	A-18	3.36										B	
	0.374	8	26	UNIF	TH -5X5	A-19	2										B	
"L" Grid	0.422	8	26	COSINE	TYP-4X4	A-20	3										A	
	0.422	14	26	USINU	TYP-4X4	A-21	3.36										A	
	0.422	8	20	USINU	TYP-4X4	A-22	3										A	
	0.422	14	26	USINU	TH -4X4	A-23	3.36										A	
	0.500	14	20	USINU	TYP-3X3	A-24	3.36										A	
								(a,c)								(a,c)		(a,c) a,

*TYP - Typical Cell

TH - Thimble Cell

2. The inclusion of the d_g term (distance from the last mixing vane grid) makes the WRB-1 correlation a stronger function of axial position than previous correlations. Provide a description of how the axial locations at which the correlation is evaluated are chosen for the CHF tests; that is, how the thermocouple locations are chosen and how the locations at which the correlation is evaluated will be chosen in the application of the correlation to reactor design and safety calculations.

Answer

The test results indicate that for uniform heat flux the CHF occurs at the exit, or the grid just upstream of the exit, while for non-uniform heat flux CHF almost invariably occurs just upstream of one or both of the last two mixing vane grids. For evaluation of the test results, the location most upstream of the exit at which a CHF signal was observed is treated as the CHF location. The thermocouple position is within a length step in which the fluid conditions are calculated; the fluid conditions calculated at the beginning of the length step in which CHF occurred are used in evaluation of the correlation. Because THINC is relatively insensitive to length steps, this is a reasonable assumption. Since this is in front of a grid, the distance from the last grid is set equal to the grid spacing. This is consistent with design use of the correlation where the elevation at the beginning of a length step containing a grid uses the grid spacing in the evaluation of the prediction of the CHF correlation.

3. What value of the performance factor (PF) is used for the 0.5 inch O.D. Rods in the 3x3 CHF tests?

<u>Answer</u>

[ ] (same as 0.422" O.D. rods). This is duscussed further in the answer to Question 7. (a,c)

4. Provide the correct value of the coefficient for the pressure squared term (B45) on page 2-5.

Answer

[ ] (a,c)

5. The Westinghouse topical report "Effects of Local Heat Flux Spikes on DNB in Non-Uniformly Heated Rod Bundles" (WCAP-8174-PA, Feb., 1975) adequately demonstrates that a special DNB heat flux spike factor need not be incorporated into the Westinghouse reactor design using Westinghouse type mixing vane grids when the W-3 CHF correlation is used. Provide a similar analysis to justify not including a special DNB heat flux spike when the WRB-1 correlation is used for reactor design.

Answer

A perturbation effect parameter, δ, (where "perturbation" refers to some small, local fuel abnormality such as a heat flux spike, a bowed rod, etc.) can be defined by:

$$\delta = 1 - \frac{(\frac{M}{P})_2}{(\frac{M}{P})_1} \equiv 1 - \frac{\frac{Q_2\ \text{meas}}{Q_2,\text{pred}}}{\frac{Q_1,\text{meas}}{Q_1,\text{pred}}}$$

where: $Q_{2,\text{meas}}$ is the measured critical heat flux in the perturbed test section (test section 2)

Q_{1},meas is the measured critical heat flux in the un-perturbed test section (test section 1).

Q_{2},pred is the critical heat flux as predicted by a correlation, based on the un-perturbed geometry of test section 1.

Q_{1},pred is the critical heat flux as predicted by a correlation for test section 1.

It should be emphasized that the heat fluxes discussed above are for two separate test runs, the second of which,carried out with the perturbed test section, was a repeat of the first, i.e., the two runs were carried out at the same inlet conditions. The two runs thus constitute a matched pair.

As a practical matter, however, the test inlet conditions cannot be matched exactly. The correlation predicted heat fluxes have been incorporated into the definition of δ in order to correct for this slight disparity in inlet conditions. This can be seen by re-writing the definition of δ:

$$\delta = 1 - \left(\frac{Q_{2,meas}}{Q_{1,meas}}\right)\left(\frac{Q_{1,pred}}{Q_{2,pred}}\right)$$

The ratio $Q_{1,pred}/Q_{2,pred}$ will thus always be close to unity since the correlation is evaluated for the same geometry in both cases, and for almost the same inlet conditions. This will be true even if the correlation predicted heat fluxes are substantially different from the measured.

Similarly, the value of $Q_{1,pred}/Q_{2,pred}$ as predicted by one correlation can be only very slightly different from that predicted by another correlation. Thus, the effect of the correlation used will be very much second order.

It should be noted that in Reference (3) the staff approved the elimination of a power spike in a completitor's plant for application with the use of a CHF correlation other than the "R" Grid and without Westinghouse mixing vane grids. The above approval was based on tests conducted by Westinghouse.

6. To date the information presented to the staff on the effects of rod bowing on DNB has been based on a combination of CHF tests and calculation using the W-3 CHF correlation. Justify the use of this information with the WRB-1 correlation or provide information on changes in CHF and the equivalent change in $F_{\Delta H}^{N}$ when the WRB-1 correlation is applied.

Answer

As described in the answer to Question 5, the effect of using the WRB-1 versus the W-3 CHF correlation is negligible.

7. Section 4 of WCAP-8762 proposes the use of a 1.17 Minimum DNBR for reactor design calculation. This value is based on 95% probability of not experiencing DNB at a 95% confidence level when all of the data are considered (i.e., 1147 data points). Since each reactor design contains only one heated length; one fuel rod size; one type of mixing vane grid, etc., the use of CHF data from CHF test on other geometries (i.e., other heated lengths, fuel rod sizes, etc.) must be justified. This justification must be based on the fact that the correlation, in combination with the subchannel code, correctly treats the physical phenomena associated with the particular geometry change. For example, the treatment of different mixing grids is accomplished by using the appropriate loss coefficients in the subchannel calculation.

No empirical constants are required in the CHF correlation in order to fit the data. Therefore the data from the "R" grid and "L" grid CHF tests can be combined when computing the mean and standard deviation of the data and in establishing the correlation limit. However, the inclusion of the "Performance Factor" (a different value for the 5x5 type fuel and the 4x4 type fuel) in the WRB-1 correlation appears to be purely empirical. The requirement for a "Performance Factor" indicates that the CHF correlation and subchannel code are not representing all of the physical phenomena associated with the hydraulic diameter, rod size, pitch, change in mixing grid geometry, etc. Provide justification for the use of both the 5x5 and 4x4 test data in establishing the correlation limit.

If combination of the 5x5 type CHF data and the 4x4 type CHF data is not adequately justified, then the DNB limits must be established independently for 5x5 type fuel and 4x4 type fuel.

Answer

The development of the WRB-1 correlation included all available data using mixing vane grids which are applicable to Westinghouse reactors. The test sections used to obtain these data were not designed to model any specific reactor core design but rather to provide a wide range of data parameters which more than cover reactor geometries and operating conditions. The WRB-1 properly accounts for the varied fluid properties and geometries encountered in twenty-four (24) different tests. This broad base for the correlation provides more versatility and justification for use of the correlation.

A subchannel code is used to determine the local fluid conditions in each subchannel at each axial elevation. The code can account for subchannel mixing and the loss coefficients of the grids. The bundle geometry change from 4x4 to 5x5 increases the number of subchannels but the solution technique of the code remains the same. The application of the THINC code to many different geometries has been extensively justified in the past; References (4, 5, 6, and 7).

As indicated in WCAP-8762, the "Performance Factor: is associated with the change in the geometry of the mixing vane grids which occurred when the rod O.D. was changed from .422" to .374". As it happens, this change also corresponds to the change from the 4x4 to 5x5 bundle. The change in geometry of the mixing vane is accounted for in the subchannel code by a change in the loss coefficients of the grid. (However, this does not fully reflect the effect of the vanes on the CHF performance of the grid. The vanes set up a swirling flow pattern around each rod. This swirl pattern delays CHF, so that the change in geometry in the mixing vane causes a change in the "Performance Factor". The swirl pattern effect is a localized phenomenon, and therefore, is independent of bundle size.) It is therefore concluded that the 4x4 and 5x5 type CHF data can be considered as part of the same population for determining CHF limits.

8. The form of the WRB-1 correlation includes a "Performance Factor" which is required to make the correlation fit both the 5x5 CHF data and the 4x4 data. The correlation indicates that the "Performance Factor" should be chosen based on the fuel rod outer diameter. This implies that the 5x5 "Performance Factor" also applies to 17x17 fuel since 17x17 fuel and the 5x5 test assembly both have rod diameters of 0.374 in. Similarly, the 4x4 "Performance Factor" would apply to 15x15 fuel. The 5x5 tests and the 4x4 tests differ in many areas, such as: rod diameter; pitch; equivalent diameter; equivalent heated diameter; mixing grid details; proximity of the CHF location to low power rods; proximity of the CHF location to the unheated walls; and proximity of the CHF location to the corner mixing vanes. A bias in CHF prediction or the subchannel conditions associated with one of these parameters could cause the difference in the 5x5 and 4x4 results. In order to apply the 5x5 and 4x4 data to 17x17 and 15x15 fuel assemblies, it is necessary to identify which of the differences between the 5x5 and the 4x4 tests causes the difference in the results (i.e., causes the need for the different "Performance Factors"). Therefore, provide a detailed discussion, inc'uding supporting calculations and test results, to justify the assumption that difference between the 5x5 and the 4x4 results is associated with difference in the rod diameter.

Answer

The identification of "Performance Factor" with a particular rod diameter was chosen as a convenient way of accounting for the change in the geometry of the mixing vane. It is not meant to imply that there is any relationship between rod diameter and "Performance Factor". Table 1 gives the vane designs for each test series. Vane design A is larger than vane design B. An appropriate method of comparing the vanes is to compare [ ]. This ratio is equal (a,c)
to [ ]^{a,c} for the type A vane and [ ]^{a,c} for the type B vane. A "Performance Factor value of [ ] is associated with the .422" rod (a,c)
because the mixing size (Vane A in Table 1) is comparable for all assemblies using this rod size and [ ] is associated with the .374" rod (a,c)
because the mixing vane size (Vane B) is comparable for all assemblies using this rod size. The change in mixing vane was not always accompanied by a rod diameter change. This is case for test A-24 where the rod O.D. was .500". The vanes were scaled to be equivalent to type A [ ]$_{a,c}$ so that the "Performance Factor" is [ ] which is the same as for .422" O.D. rods. The results (a,c)
of this test are in good agreement with all the other tests.

The 5x5 test bundle has grids which are exact duplicates of the 17x17 fuel assembly grids. The 4x4 test bundle has a ^{a,c}[ ] which is equal to the 15x15 fuel assembly vane design.

9. For test series A-3, WCAP-8762 indicates that for some cases, the CHF location was measured at 84 inches from the test section inlet. WCAP-8536 which is referenced as the source of the information for test series A-3 shows the thermocouple location to be 85 inches from the inlet. Correct this discrepancy.

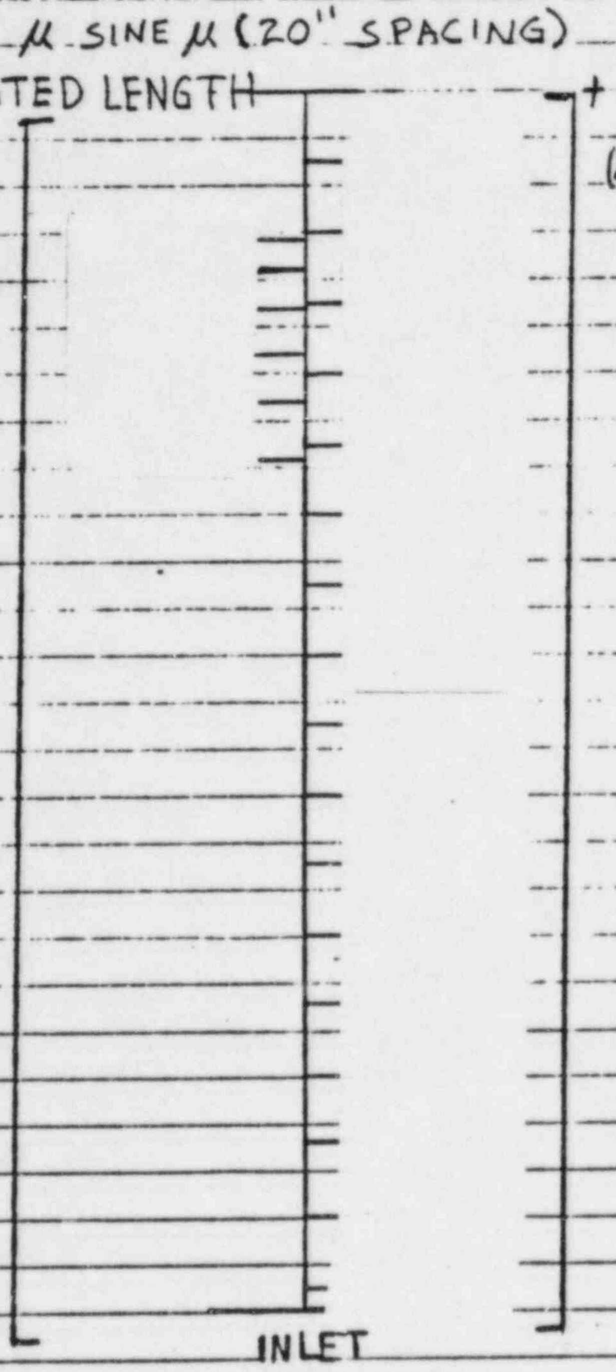
Answer

The thermocouple was located at 85 inches from the inlet in test series A-3 while the measured location was indicated as 84 inches. This discrepancy is the result of the axial nodalization used in the data analysis. The length step containing the T/C location (85 in.) is treated as having CHF occurring at the beginning of the length step. This is consistent with the design procedure as outlined in the answer to question 2.

10. Provide the grid locations and thermocouple locations for the test series A-10. This information is not presently available because these tests were not previously published.

Answer

Figure 2 gives the locations of the grids and thermocouples for test series A-10.



MV - MIXING VANE GRID
SS - SIMPLE SUPPORT GRID
TC - THERMOCOUPLE - CHF DETECTOR

DISTANCES REFERRED TO BEGINNING OF HEATED LENGTH

FIGURE 2. AXIAL GRID AND CHF DETECTOR LOCATION FOR 14 FT. TEST SECTION WITH 20" GRID SPACING

11. The staff has been unable to verify the results of the A-10 test series. We believe that this is because the USINU power distribution presented in WCAP-8762 and in the referenced reports does not have sufficient detail to allow an accurate representation in the COBRA IV code. Provide a more detailed graphical or numerical representation of the power distribution for test series A-10.

Answer

The axial heat flux profiles for test series A-10 are the same as for test series A-9, A-11, A-12, A-14, A-16 and A-17. Figure 3 is a plot of this profile.

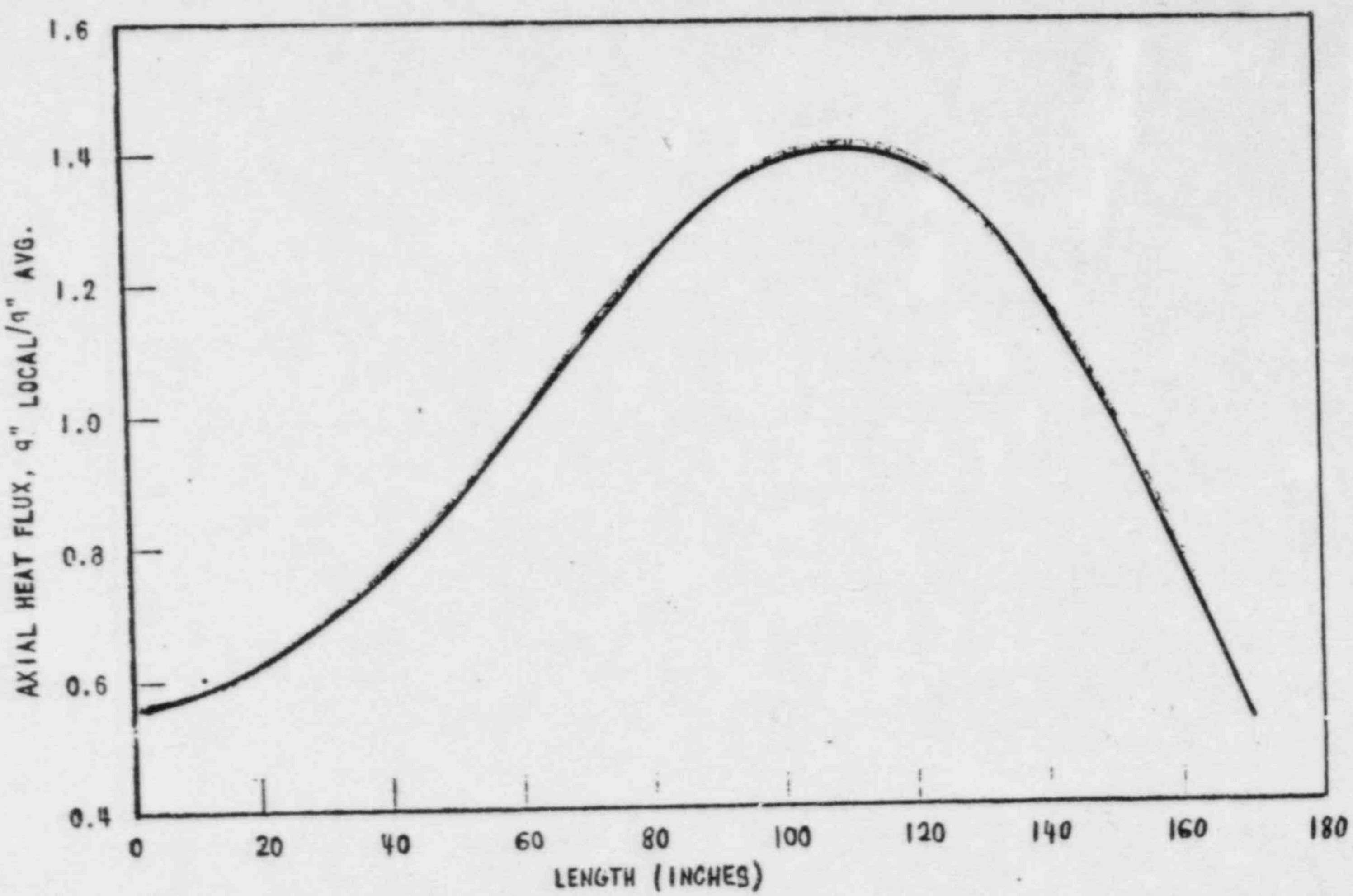


Figure 3. 14 Ft. Heater Rods Axial Heat Flux Distributions

REFERENCES

1. Motley, F. E., Hill, K. W., Cadek, F. F., Shefcheck, J., "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids," WCAP-8762, (Westinghouse proprietary), July 1976.

2. Novendstern, E. H. and Sandberg, R. O., "Single Phase, Local Boiling and Bulk Boiling Pressure Drop Correlations", WCAP-2850-L, April 1966 (Westinghouse Proprietary).

3. Docket No. 50-255, Amendment 21 to Provisional Operating License DPR-20, United States Nuclear Regulatory Commission, April 29, 1976

4. H. Chelemer, J. Weisman and L. S. Tong, "Subchannel Thermal Analysis of Rod Bundle Core," WCAP-7015, Revision 1, January, 1969.

5. J. Shefcheck, "Application of the THINC Program to PWR Design," WCAP-7359-L, August, 1969, (Westinghouse Proprietary), and WCAP-7838, January, 1972.

6. L. E. Hochreiter, H. Chelemer and P. T. Chu, "THINC-IV An Improved Program for Thermal-Hydraulic Analysis of Rod Bundle Core," WCAP-7956, June, 1973.

7. L. E. Hochreiter, "Application of the THINC IV Program to PWR Design," WCAP-8054, October, 1973, (Westinghouse Proprietary), and WCAP-8195, October, 1973.

Westinghouse Electric Corporation
Water Reactor Divisions
Box 355
Pittsburgh Pennsylvania 15230

November 18, 1983

NS-EPR-2854

Dr. Cecil O. Thomas, Chief
Special Projects Branch
Division of Project Management
U.S. Nuclear Regulatory Commission
Phillips Building
7920 Norfolk Avenue
Bethesda, Maryland 20014

SUBJECT: Basis for the Applicability of the WRB-1 CHF Correlation to 15x15 OFA and 14x14 OFA Fuel, Supplement 1, WCAP-8762 (Proprietary)

REFERENCE: "New Westinghouse Correlation WRB-1 for Predicting CHF in Rod Bundles with Mixing Vanes," WCAP-8762 (Proprietary)

Dear Dr. Thomas:

Enclosed are twenty-five (25) copies of, "Basis for Applicability of the WRB-1 CHF Correlation to 15x15 OFA and 14x14 OFA Fuel," Supplement 1 to WCAP-8762 (Proprietary).

Also enclosed are:

1. Fifteen (15) copies of, "Basis for Applicability of the WRB-1 CHF Correlation to 15x15 OFA and 14x14 OFA Fuel," Supplement 1 to WCAP-8763 (Non-Proprietary).

2. One (1) copy of Application for Withholding (Non-Proprietary).

3. One (1) copy of Affidavit (Non-Proprietary).

This information is provided to gain generic approval for using the WRB-1 CHF Correlation to evaluate 15x15 OFA and 14x14 OFA fuel designs. In this regard we anticipate a Supplement to the SER for WCAPs 8762 and 8763.

Expedited NRC review and approval is requested to support near term OFA reload applications.

This submittal contains proprietary information of Westinghouse Electric Corporation. In conformance with the requirements of 10CFR2.790, as amended, of the Commission's regulations, we are enclosing with this submittal an application for withholding from public disclosure and a copy of an affidavit. The affidavit sets forth the basis on which the information may be withheld from public disclosure by the Commission.

Correspondence with respect to the affidavit or the application for withholding should reference AW-83-101 and should be addressed to R. A. Wiesemann, Manager of Regulatory and Legislative Affairs, Westinghouse Electric Corporation, P.O. Box 355, Pittsburgh, Pennsylvania 15230.

Very truly yours,

for E. P. Rahe, Jr., Manager
Nuclear Safety Department

JWM/kk
Enclosures

cc: Mr. Carl H. Berlinger, Chief
Core Performance Branch
Division of Systems Integration

Mr. Laurence E. Phillips
Core Performance Branch

SUPPLEMENT 1 TO WCAP-8763

Basis for the Applicability of the WRB-1 Correlation to 15x15 OFA and 14x14 OFA Fuel.

Section	Title
A.	15x15 OFA Fuel
B.	14x14 OFA Fuel

A. 15x15 OFA FUEL

INTRODUCTION

The WRB-1 CHF correlation is based entirely on rod bundle data and has been shown to provide a significant improvement in DNB predictive capability for Westinghouse fuel designs with type "R" mixing vane grids. The NRC has recognized this increased accuracy and concurred that a 95/95 limit DNBR of 1.17 is appropriate for 12 ft and 14 ft 17x17 standard and optimized fuel assemblies, and 12 ft 15x15 standard fuel assemblies with the type "R" mixing vane grid (Ref. 1 and 2). Based on the semi-empirical nature of the correlation, the NRC has imposed restrictions on its applicability to other PWR designs. Specifically, the Safety Evaluation Report stated that. "The correlation should not be applied to any PWR geometry which has not been specifically tested or which has not been bracketed by the test data. The important parameters to which this applies are: rod size, rod pitch, heated length, mixing vane design and grid spacing."

The 15x15 optimized design is virtually identical to the 15x15 R-grid design in that the [

]$^{+}$ (a,c)

As will be discussed below, similar scaling techniques have been used for designing the 17x17 OFA and 14x14 OFA grids, and DNB testing has shown that the WRB-1 correlation correctly predicts the performance of those designs without modifications.

17x17 OFA DNB TEST RESULTS

Geometrically the 17x17 OFA design differs from the standard 17x17 R-grid design in that:

1) The fuel rod diameter was reduced from 0.374 inch to 0.360 inch.

2) The Zircaloy type "R" grid is taller and has a thicker strap than the Inconel type "R" grid which has previously been DNB tested.

In order to minimize the effect of the grid dimensional changes on DNB performance, special care was taken to preserve the important type "R" mixing vane characteristics. [(a,c)

]+ DNB testing of the 17x17 OFA geometry demonstrated the success of this scaling approach--the WRB-1 correlation predicted the data well without any modifications, using the same performance factor as was used for the 17x17 standard fuel. Repeatability studies (Ref. 3) have shown that the accuracy of the WRB-1 correlation is essentially identical for the 17x17 OFA and standard geometries, indicating that no additional component of variance is introduced by the grid dimensional changes. In other words, the correlation correctly accounted for the equivalent diameter effects and the scaling approach correctly accounted for the grid dimensional changes.

14X14 OFA DNB TEST RESULTS

The 14x14 optimized geometry differs from the reference geometry in that:

1) The fuel rod diameter has been reduced from 0.422 inch to 0.400 inch.

2) The Zircaloy type "R" grid is taller and has a thicker strap than the Inconel type "R" grid which had previously been DNB tested.

A DNB test series of the 14x14 OFA typical cell geometry has been performed to verify that the WRB-1 correlation correctly predicts the effect on CHF of the equivalent diameter change, and that the grid scaling approach introduces no additional component of variance. The details of the 14x14 OFA test, including test section description, test procedures, data, and data evaluations are presented in Section B of this submittal.

The results indicate that the WRB-1 correlation predicts the 14x14 OFA data with essentially the same accuracy as for the geometry from which it was scaled. The average measured-to-predicted critical heat flux ratio for the data set is 1.0571 with a sample standard deviation of 0.0771. These values were compared to those from the 0.422 inch rod bundle tests with 26 inch grid spacing, the geometry from the original WRB-1 R-grid database which is closest to the 14x14 OFA geometry. As shown in Table 1 the agreement is excellent, indicating that the WRB-1 correlation correctly accounts for the geometry changes. Also given in Table 1 is a comparison of the 17x17 standard and OFA DNB statistics. It is apparent that the WRB-1 correlation's ability to predict CHF is essentially identical for standard and OFA fuel designs.

STATISTICAL TESTS

T-tests and F-tests have been performed for each of these standard/OFA data set pairs in order to evaluate the effect of the geometry changes on the accuracy of the WRB-1 correlation. Table 2 shows the results of these tests. It can be seen that the hypothesis that the WRB-1 correlation predicts the DNB behavior of the OFA geometries with the same accuracy as the standard R-grid geometries cannot be rejected at a 5% significance level, with the exception of the [ ]+ (b,c) comparison. For that comparison the OFA data had an appreciably lower variance. A smaller variance is indicative of better correlation accuracy, so failure of the F-test is no reason for concern. Therefore, the results of these tests indicate that no additional component of variance is introduced by the grid dimensional changes.

OTHER GRID SIMILARITIES

One difference between the 15x15 OFA design and the 14x14 and 17x17 OFA designs is that in the 14x14 and 17x17 cases, there was a rod diameter change from their respective standard designs as well as the change to a Zircaloy grid, while in the 15x15 case there was no rod diameter change. This has raised the NRC concern that there may be a different flow velocity effect in the grid of the 15x15 OFA design as compared to the 14x14 and 17x17 designs that were tested. Included in Table 1 for the various geometries is the ratio of the gridded flow area to the ungridded flow area. Ungridded flow area refers to the bundle flow area at an ungridded elevation. Gridded flow area is the projected flow area at a grid elevation, i.e. bundle flow area minus obstructions due to grid straps, springs, dimples, etc. The ratio of these two flow areas gives an indication of the velocity changes encountered by the fluid as it passes through a grid. As can be seen in Table 1, both the 14x14 and 17x17 OFA designs resulted in

[

]+ (a,c)

CONCLUSICNS

Based on the similarity of the 15x15 OFA and R-grid geometries and the previous success of the scaling techniques employed in the Zircaloy grid design (as demonstrated by the 17x17 OFA and 14x14 OFA DNB test results), it is concluded that the use of the WRB-1 CHF correlation with a design limit of 1.17 for the 15x15 OFA design is appropriate and that no additional uncertainty is required.

REFERENCES

1) Letter, D. F. Ross, Jr. (NRC) to D. B. Vassalo (NRC), Subject: Topical Report Evaluation for WCAP-8762, April 10, 1978.

2) Letter, R. L. Tedesco (NRC) to T. M. Anderson (Westinghouse), Subject: Acceptance for Referencing Topical Report WCAP-9401 (P)/WCAP-9402 (NP), May 7, 1981.

3) Beaumont, M. D., Skaritka, J., "Verification Testing and Analyses of the 17x17 Optimized Fuel Assembly," WCAP-9401, March 1979.

TABLE 1

STATISTICAL COMPARISON OF STANDARD AND OPTIMIZED FUEL
CHF RESULTS USING THE WRB-1 CORRELATION

+b,c

TABLE 2

F-test and t-test Results for Standard/OFA

Data Set Pairs in Table 2

[ ]+b,c

B. 14x14 OFA FUEL

INTRODUCTION

The 14x14 optimized geometry differs from the reference geometry in that:

1) The fuel rod diameter has been reduced from 0.422 inch to 0.400 inch.

2) The Zircaloy type "R" grid is taller and has a thicker strap than the Inconel type "R" grid which had previously been DNB tested.

In order to ensure that these changes do not affect DNB performance, special care was taken to preserve the important type "R" mixing vane characteristics. [

]+ Similar (a,c)
scaling techniques have also been used in designing the 17x17 and 15x15 OFA grids.

CRITICAL HEAT FLUX TESTING

DNB testing of the 17x17 OFA geometry initially demonstrated the success of this scaling approach -- the WRB-1 correlation (Ref. 1) predicted the data well without any modifications, using the same performance factor as was used for the 17x17 standard fuel (Ref. 2).

These results indicate that the correlation correctly accounted for the equivalent diameter effects and the scaling approach correctly accounted for the grid dimensional changes.

A DNB test series of the 14x14 OFA typical cell geometry has been performed to verify that the WRB-1 correlation predicts the 14x14 OFA DNB performance with essentially the same accuracy as for the geometry from which it was scaled. As discussed below, the results of this test series provide further verification of the scaling techniques employed in the Zircaloy grid design.

TEST FACILITIES

The test facilities and testing procedures used for the 14x14 OFA DNB tests were the same as those described in References 3 and 4. The test section was similar to the 0.422 inch rod bundle described in Reference 3, except that the mixing vane grid dimensions were modified slightly in order to accommodate the new rod diameter and the change from Inconel to Zircaloy. The modified grid design has retained the type "R" grid features. Figure 1 shows a sketch of the 14x14 OFA typical cell test bundle cross section. The axial locations of the grids and thermocouples are shown in Figure 2, and Figure 3 shows the cosine axial power distribution used for the tests.

14x14 OFA DNB DATA EVALUATIONS

The data were reduced using the THINC subchannel code, in the same manner as described previously in References 3 and 4. The WRB-1 correlation of Reference 1 was used to predict the critical heat flux.
[

]+ As (a,b,c)
shown in Reference 2, this approach had previously worked quite well with the 17x17 OFA DNB data.

The results of the data reduction are shown in Table 1. The average measured-to-predicted critical heat flux ratio for the data set is 1.0571 with a sample standard deviation of 0.0771. These values were compared to those from the 0.422 inch rod bundle tests with 26 inch grid spacing, the geometry from the original WRB-1 R-grid database which is closest to the 14x14 OFA geometry. As shown in Table 2, the agreement is excellent, indicating that the WRB-1 correlation correctly accounts for the geometry changes and that the choice of performance factor is appropriate. Also given in Table 2 is a comparison of the 17x17 standard and OFA DNB statistics. It is apparent that the WRB-1 correlation's ability to predict CHF is essentially identical for standard and OFA fuel designs.

CRITERION FOR DESIGN

Because the 14x14 OFA data set is indistinguishable from the 0.422 inch rod data sets with the same grid spacing, this new set can be incorporated into the data base of the WRB-1 correlation of Reference 2. This is done in Table 3 which includes all the "R" grid data of Reference 2 plus the new data set of this study.

As shown in Table 3, this expanded "R" grid data base yields statistics for the WRB-1 correlation which are essentially the same as those given in Reference 2. When values of $(M/P)_{avg}$ and sample standard deviation, S, are used to calculate the 95/95 value of DNBR using the method of Owen (Reference 5), the result is:

$$(DNBR)_{95/95} = \frac{1}{(\frac{M}{P})_{avg} - KS} = \frac{1}{1.0079 - 1.724(0.0859)}$$

where K is a statistical factor (Reference 5)

$$(DNBR)_{95/95} = 1.163$$

This is essentially the same value (1.17) found for the "R" grid data of Reference 2. Hence, the design $(DNBR)_{95/95}$ = 1.17 recommended in Reference 2 is not changed by the incorporation of the new optimized fuel 14x14 data into the "R" grid data base of the WRB-1 correlation.

CONCLUSIONS

DNB testing of the 14x14 OFA typical cell geometry has shown that the WRB-1 correlation correctly accounts for the geometry changes from the reference design, using the same performance factor as used for the 0.422 inch rod data evaluations. The 14x14 OFA data can be added to the WRB-1 R-grid database without changing the DNBR limit of 1.17.

REFERENCES

1. Motley, F. E., Hill, K. W., Cadek, F. F., Shefcheck, J., "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids," WCAP-8762, (Westinghouse Proprietary), July 1976.

2. Beaumont, M. D., Skaritka, J., "Verification Testing and Analyses of the 17x17 Optimized Fuel Assembly," WCAP-9401, March 1979.

3. K. W. Hill, F. E. Motley, F. F. Cadek, A. H. Wenzel, "Effect of 17x17 Fuel Assembly Geometry on DNB," WCAP-8926-P-A (Westinghouse Proprietary) and WCAP-8297-A (Non-proprietary), February 1975.

4. F. E. Motley, A. H. Wenzel, F. F. Cadek, "Critical Heat Flux Testing of 17x17 Fuel Assembly Geometry with 22-Inch Grid Spacing," WCAP-8536, (Westinghouse Proprietary) and WCAP-8537 (Non-proprietary), May 1975.

5. D. B. Owen, "Factors for One-Sided Tolerance Limits and for Variable Sampling Plans," SCR-607, March 1963.

FIGURE 1

+b,c

FIGURE 2

AXIAL GRID AND CHF DETECTOR LOCATIONS,
14X14 OPTIMIZED CHF TEST SECTION

+b,c

Q''_{LOC}/Q''_{AVG}: LOCAL-TO-AVERAGE HEAT FLUX RATIO

a,b,c

Z, AXIAL DISTANCE FROM BEGINNING OF HEATED LENGTH (INCHES)

Figure 3. Axial Heat Flux Distribution

TABLE 1 - CHF TEST RESULTS FOR 14x14 OFA TYPICAL CELL USING WRB-1 CORRELATION

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (P)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	M/P CHF (WRB-1)	ELEVATION FROM INLET (INCHES) PRED.	MEAS. a,b,c
W2242							1.0599		
W2243							1.1582		
W2244							1.0593		
W2245							1.1064		
W2246							1.1149		
W2247							1.1483		
W2248							1.0943		
W2249							1.1320		
W2250							1.1482		
W2251							1.1118		
W2252							.9741		
W2253							1.1036		
W2254							1.0983		
W2255							1.0939		
W2256							1.0844		
W2257							1.0783		
W2258							1.1018		
W2259							.9514		
W2260							1.1338		
W2261							1.0550		
W2262							.8592		
W2263							.9104		
W2264							.9466		
W2265							1.0739		
W2266							1.0461		
W2267							.9942		
W2268							1.0154		
W2269							1.0146		
W2270							1.0065		
W2271							.9615		

TABLE 1 (CONTINUED)

CHF TEST RESULTS FOR 14x14 OFA TYPICAL CELL

RUN NO.	INLET PRESSURE (PSIA)	INLET TEMP (F)	INLET MASS VELOCITY (X10E6 LBM/HR-SQFT)	LOCAL QUALITY (%)	LOCAL HEAT FLUX (X10E6 BTU/HR-SQFT) MEAS.	PRED.	M/P CHF (WRB-1)	ELEVATION FROM INLET (INCHES) PRED.	MEAS. +b,c
W2272							1.1481		
W2273							1.0612		
W2274							.9741		
W2314							.9314		
W2315							1.0735		
W2316							1.1411		
W2317							1.1465		

L = 14 FT
DE = .5840 IN
4 RODS 100%
12 RODS 85%

ROD O.D. = [ ] +a,c
ZIRC SPRING MV GRIDS 26 IN SPACING
INNER ROD/OUTER ROD POWER = 1.1765

TABLE 2

STATISTICAL COMPARISON OF STANDARD AND OPTIMIZED FUEL
CHF RESULTS USING THE WRB-1 CORRELATION

+b,c

TABLE 3

WRB-1 CHF CORRELATION - STATISTICAL RESULTS USING ALL "R" GRID DATA, INCLUDING NEW OPTIMIZED 14x14 DATA

Rod O.D. Inch	L_H ft	g_{sp} Inch	Heat Flux Profile	Configuration[a]	N	$(\frac{M}{P})_{avg}$	Sample Standard Deviation, S	Reference
0.374	14	22	UNIF	TYP - 5x5	71	0.9964	0.0655	(2)
0.374	14	26	UNIF	TYP - 5x5	73	1.0041	0.0805	
0.374	8	22	UNIF	TYP - 5x5	67	1.0502	0.1020	
0.374	8	26	UNIF	TYP - 5x5	78	1.0136	0.0848	
0.374	14	22	COSINE	TYP - 5x5	74	1.0022	0.0852	
0.422	8	20	COSINE	TYP - 4x4	33	1.0042	0.0528	
0.422	8	20	USINU	TYP - 4x4	33	0.9937	0.0649	
0.422	8	26	USINU	TYP - 4x4	36	0.9846	0.0922	
0.422	14	26	USINU	TYP - 4x4	35	1.0584	0.0816	
422	14	20	USINU	TYP - 4x4	36	1.0100	0.0915	
0.422	14	13	USINU	TYP - 4x4	38	0.9737	0.0781	
0.422	14	32	USINU	TYP - 4x4	38	1.0238	0.0752	
0.422	8	32	USINU	TYP - 4x4	31	0.9913	0.0724	
0.422	14	26	USINU	TYP - 4x4	71	1.0466	0.0829	
0.422	14	26	UNIF	TYP - 4x4	42	0.9321	0.0595	
0.422	14	26	USINU	TH - 4x4	39	1.0141	0.0579	
0.422	14	32	USINU	TH - 4x4	37	0.9738	0.0887	
0.374	14	22	COSINE	TH - 5x5	70	1.0002	0.0796	
0.374	8	26	UNIF	TH - 5x5	68	1.0303	0.1048	
0.360	14	20	COSINE	TYP - 5x5	63	0.9918	0.0970	
0.360	14	20	COSINE	TH - 5x5	38	0.9755	0.0504	
[ ]+(b,c)	14	26	COSINE	TYP - 4x4	37	1.0571	0.0771	This study
			ALL DATA+		1180	1.0079	0.0859	

+Results use all "R" grid data, including new optimized 14x14 data

*TYP - Typical Cell

TH - Thimble Cell