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Addendum 2
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Addendum 2 to WCAP-15306-NP-A Extended Application of ABB-NV Correlation and Modified ABB-NV Correlation WLOP for PWR Low Pressure Applications

Westinghouse

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Addendum 2 to WCAP-15306-NP-A Extended Application of ABB-NV Correlation and Modified ABB-NV Correlation WLOP for PWR Low Pressure Applications

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Abstract

This report describes: 1) the extension of the ABB-NV Critical Heat Flux (CHF) correlation applications to the non-mixing vane (NV) grid region of the Westinghouse Pressurized Water Reactor (PWR) fuel designs, and 2) the modification of the ABB-NV correlation based on low pressure rod bundle data. The modified correlation for low pressure applications is designated the WLOP correlation. Similar to the W-3 CHF correlation, ABB-NV will be used for predicting DNBR margin in the NV grid region to supplement the primary DNB correlation for Westinghouse PWR fuel designs with mixing vane (MV) grids. The WLOP correlation will be used for predicting DNBR margin at low pressure conditions that is typically encountered in a steamline break (SLB) accident analysis, as an alternative to W-3 or MacBeth correlations for Westinghouse PWR plants and Combustion Engineering PWR (CE-PWR) plants.

The ABB-NV correlation has previously been approved for application for CE-PWR plants with both the TORC code and Westinghouse version of the VIPRE-01 code (VIPRE) thermal hydraulic codes. Supplemental rod bundle data evaluation confirms the current ABB-NV correlation 95/95 DNBR limit of 1.13 with VIPRE for the NV grid region for Westinghouse PWR fuel designs. The supplemental data evaluation extends the applicable range of the ABB-NV correlation.

The WLOP correlation is a modified ABB-NV correlation specifically for low pressure conditions and extended flow range to cover low flow conditions. Modifications to the ABB-NV correlation form were made using existing CHF data from rod bundles with NV grids, incorporating many of the tests included in the ABB-NV correlation. The WLOP coefficients were derived based on fluid conditions from VIPRE calculations. The WLOP 95/59 DNBR limit is determined to be 1.18 with the VIPRE code for both Westinghouse PWR and CE-PWR fuel designs. The WLOP 95/95 DNBR limit is also qualified with test data from rod bundles containing MV grids simulating Westinghouse PWR fuel designs.

The range of applicability for each correlation:

Parameter	**ABB-NV Extension**	**WLOP**
Pressure (psia)	1750 to 2415	185 to 1800
Local mass velocity (Mlbm/hr-ft^2)	0.8 to 3.16	0.23 to 3.07
Local quality	≤ 0.22	≤ 0.75
Heated length, inlet to CHF location (in)	48* to 150	48* to 168
Grid distance, (in)	7.3 to 24	
Grid spacing term, GST		27 to 115
Heated hydraulic diameter ratio, [ ]^{a,c}	0.679 to 1.08	0.679 to 1.00

* **Set as Minimum HL value, applied at all elevations below 48 inches**

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1.0 Introduction

The ABB-NV correlation was developed based on CHF data of rod bundles obtained from the Heat Transfer Research Facility of Columbia University for Pressurized Water Reactor (PWR) 14x14 and 16x16 fuel designs containing structural non-mixing vane grids. A CHF correlation is also commonly referred to as a Departure from Nucleate Boiling (DNB) correlation in PWR safety analyses. The ABB-NV correlation has been approved for application for fuel designs containing non-mixing vane (NV) grids for Combustion Engineering PWR (CE-PWR) with both the Westinghouse TORC computer code(1) and the Westinghouse version of the VIPRE-01 (VIPRE) code(2)(3). The SER on the VIPRE application(3) stated that VIPRE is equivalent to TORC for the ABB-NV correlation under the conditions that DNBR calculations for CE-PWR fuel designs are within the current applicable range.

Currently, the W-3 correlation is used for predicting DNBR margin in the NV grid region to supplement the primary DNB correlation for Westinghouse PWR fuel designs with mixing vane (MV) grids. The W-3 correlation is also used to supplement the primary DNB correlation for DNBR calculation at the low pressure conditions from PWR post-trip steamline break (SLB) events (also referred to as Hot Zero Power (HZP) SLB events) as well as low flow and low pressure conditions from a post-trip SLB without offsite power event(5). The W-3 correlation was developed in the 1960's from single tube and annular geometry. The W-3 correlation has been validated to be conservative for rod bundles for current design applications, but its DNBR predictions are not very accurate as reflected in the relatively high 95/95 DNBR limits(5). For CE-PWR plants, the MacBeth correlation is conservatively used for DNBR calculation at the low pressure conditions for post-trip (HZP) SLB accident analysis (6).

The ABB-NV correlation was developed exclusively from rod bundle data with PWR NV grids, and therefore it provides more accurate DNBR predictions than W-3. A modification to the ABB-NV correlation is made based on rod bundle data at low pressure and low flow conditions. The modified low pressure ABB-NV correlation is designated as the WLOP (Westinghouse Low Pressure) correlation in this report. The WLOP correlation predicts more accurate DNBR than either W-3 or MacBeth correlation at the low pressure and low flow conditions.

This addendum describes qualifications of the extended application of ABB-NV and the WLOP correlation as an alternative to W-3 or MacBeth, in supplement to the primary DNB correlation for Westinghouse PWR fuel designs with Westinghouse version of the VIPRE code(2)(3). It provides:

1. Justification on the use of the ABB-NV correlation for the non-mixing grid region of Westinghouse PWR with no change to the correlation form, its coefficients and the currently licensed 95/95 DNBR limit(3)(4).
2. Development and validation of the WLOP correlation and the proposed 95/95 DNBR limit for low pressure and low flow conditions.

The justification of extending the ABB-NV correlation to Westinghouse PWR fuel designs is based on the demonstration of the applicability of the ABB-NV correlation to supplemental non-mixing vane data from CHF tests with rod diameters of 0.36 and 0.374 inches. The applicable range of pressure, flow and the maximum quality limit approved in the SER(3)(4) is maintained.

The WLOP correlation is a modified ABB-NV correlation specifically for low pressure conditions. Modifications to the ABB-NV correlation form were made using existing CHF data from rod bundles with non-mixing vane grids, incorporating many of the tests included in the ABB-NV correlation. The correlation data with non-mixing vane grids were obtained for test section heated lengths ranging from 48 inches to 150 inches, grid spacing of 8.0 inches to 21.5 inches, rod diameter ranging from 0.374 inches to 0.440 inches, flows above 0.15 Mlb/hr-ft^2, and pressures above 185 psia. The WLOP coefficients were derived based on fluid conditions from VIPRE calculations.

A description of the CHF tests used to demonstrate the applicability of the ABB-NV correlation for the non-mixing grid region of Westinghouse PWR fuel designs is given in Section 2 of this addendum. A description of the CHF tests supporting the modified ABB-NV correlation, WLOP, is also summarized in Section 2. Available mixing grid CHF tests are also examined to demonstrate the applicability of the WLOP correlation to mixing vane designs.

Section 3 provides a description of the VIPRE modeling of the CHF tests used to demonstrate the applicability of ABB-NV correlation for the NV grid region for the Westinghouse PWR fuel designs and the results compared to the correlation results for CE-PWR with VIPRE presented in Reference 3.

Section 4 describes the modification of the ABB-NV correlation form for application at low flow and low pressure conditions and the optimization of the coefficients for the WLOP correlation and the validation of the correlation. VIPRE was used to compute the local coolant conditions in the CHF test sections.

Section 5 summarizes the statistical evaluation for the ABB-NV correlation with the supplemental qualification test data presented in this report and the statistical evaluation for the modified correlation, WLOP. The evaluations confirmed the current 95/95 DNBR limit of the ABB-NV for the extended application, and determined a 95/95 DNBR limit for the WLOP application.

Section 6 discusses how the ABB-NV and WLOP CHF correlations will be applied in plant safety or reload analyses. Conclusions are presented in Section 7 and References are given in Section 8.

A detailed summary of the ABB-NV qualification database for the NV grid region of Westinghouse PWR is given in Appendix A. The statistical output of the ABB-NV correlation for the qualification database is given in Appendix B. A detailed summary of the WLOP correlation and validation database for the low flow and low pressure conditions is given in Appendix C. The statistical output of the WLOP correlation is given in Appendix D. A detailed summary of the test section radial and axial power distributions for the WLOP correlation is given in Appendix E.

2.0 Description of CHF Test Programs and Test Section Geometry

A description of the original CHF experiments and test section geometry for the ABB-NV correlation is given in Reference 4. Two supplemental tests were selected to demonstrate that the ABB-NV correlation is applicable for the region of Westinghouse PWR fuel designs below mixing vane grids at the core inlet. One rod bundle test, identified as Test 190, was performed on a brazed Inconel NV grid design with 21.5 inch grid spacing at Columbia University's Heat Transfer Research Facility in the 1980's. The second test, identified as Test 175, was taken from the open literature(7). Test 175 was performed on a NV grid design in a hexagonal rod bundle with similar rod and hydraulic diameter dimensions as the Westinghouse PWR with 0.360-inch diameter rods and 0.496–inch rod pitch.

The CHF experiments for the modified ABB-NV correlation for low pressure conditions (WLOP) were conducted at Columbia University's Heat Transfer Research Facility. The WLOP correlation is based upon a re-evaluation of CHF data from rod bundle tests that spanned the period from 1971 to 1982. CHF tests used to demonstrate applicability for mixing vane grids were performed up to the 1990's. A detailed description of the facility for the WLOP tests can be found in Reference 8. A description of the test loop and data acquisition system used for the supplemental tests is provided in Reference 4.

2.1 Description of Supplemental ABB-NV Test Sections

For the non-mixing grid region of Westinghouse PWR fuel designs below the first mixing vane grid, the ABB-NV correlation is applicable, since most parameters are within the applicable ranges specified in the SER(3). Although the NV grid region is less than 30 inches in a typical Westinghouse fuel design, additional conservatism is added to the correlation application by maintaining the minimum heated length to be 48 inches. The Westinghouse PWR designs with 0.422-inch diameter fuel rods fall within the tested rod diameters in the ABB-NV correlation. The Westinghouse PWR fuel designs with 0.374-inch diameter fuel rods and 0.360-inch diameter fuel rods are slightly outside the rod dimensions in the ABB-NV database(3)(4) and the grid spacing is somewhat greater than the grid spacing in the original database. The qualification database was selected for those rod diameters with different grid spacing to demonstrate that the ABB-NV correlation with its existing grid spacing term was sufficiently robust to predict test data of fuel geometry somewhat outside the original correlation range. A summary of the test section geometry for the supplemental tests is shown in Table 2-1.

The Test 190 test section simulates a 5x5 array of a 17x17 fuel design with heated rods of 0.374 inch O.D. in a 0.500 inch rod pitch with NV grids. The grid has straight strap design with 12-mil strap thickness and the test was performed with 21.5 inch nominal grid spacing. The radial geometry for this test section is shown in Figure 2-1. The power split between the cold rods and hot rods for this test was approximately [ ] ^{a,b,c}. The axial locations of the test grids and rod thermocouples for Test 190 are given in Figure 2-2.

Test 175 was taken from the open literature(7) and simulates a seven-rod bundle in a triangular array. This test was selected since it provided data with heated rod diameter near 0.360 inches (0.358-inch rod diameter) and a rod pitch of 0.496 inches. DNB tests previously performed by Westinghouse from grid-spaced rod bundles show no significant difference in CHF between a square array and a triangular array with similar rod and hydraulic diameter dimensions(20). The radial geometry for this test section is shown in Figure 2-3. The power split between the cold rods and hot rods for this test was 1.0. The axial locations of the test grids and rod thermocouples for Test Section 175 are given in Figure 2-4. It is noted that the distance from grid, DG, from the last grid to the end of heated length (EOHL) is 7.3 inches although the nominal grid spacing is 9.45 inches. ABB-NV predictions in good agreement with the CHF data from a rod bundle in a hexagonal lattice demonstrate that the correlation is sufficiently robust to cover different geometries for non-mixing vane grids.

2.2 Description of WLOP Test Sections

The data used for the development and validation of the WLOP correlation were obtained from eighteen test bundles with a uniform axial power shape. The test sections, described in Table 2-2, simulate a 5x5 array of fuel assembly geometries without mixing vanes. Thirteen of these test sections are representative of a 14x14 fuel assembly geometry (0.440 inch O.D. heated rods and 0.580 inch rod pitch), four test sections are representative of a 16x16 fuel assembly geometry (0.382 inch O.D. heated rods and 0.506 inch rod pitch) and one test section is representative of a 17x17 fuel assembly geometry (0.374 inch O.D. heated rods, 0.500 inch rod pitch) with brazed Inconel grids. It is noted that high pressure data from seven tests, Tests 18, 21, 36, 38, 43, 47 and 51, were used in the development of the ABB-NV correlation and the test specific geometry has already been documented in Reference 4.

Twelve of the tests were conducted with a simulated guide thimble. Tests were run with the simulated guide thimble placed either near the center of the test section surrounded by heated rods or adjacent to the test shroud. Typical radial geometries for the 14x14 test sections, with and without a guide thimble, are shown in Figures 2-5 through 2-7, respectively. A typical radial geometry for the 16x16 test sections with a guide thimble is shown in Figure 2-8. The radial geometry for the 17x17 geometry without a guide thimble is shown in Figure 2-1. The power split between the cold rods and hot rods ranged from [ ]^{a,b,c}. The radial power distributions for the individual tests not included in the ABB-NV correlation are given in Appendix E. The axial geometries for these individual tests are also given in Appendix E. A summary of the test section geometry for the eighteen tests is shown in Table 2-2. The data from the source or "correlation" test sections were used to develop the coefficients for the WLOP correlation following the ABB-NV correlation form with modifications to the form as discussed in Section 4.0. The data from the "validation" test sections were used in the evaluation of the correlation. Test sections were selected to provide data at the low flow, low pressure conditions and to cover the range for the geometric parameters such as heated length, grid spacing, and heated hydraulic diameter.

The test grids for all the tests are similar to the reactor design. The standard grids were manufactured with Zircaloy-4 material for the early tests. The stronger Inconel 625 material was used in later tests to provide improved support for the heater rods. The grid material change does not affect CHF performance of the grid design. To provide additional support for the 150" heated length tests, the test grid springs were reinforced. The use of the reinforced spacer grids was justified in Appendix D of Reference 8. The test with the 0.374 inch diameter rods was performed with Inconel grids. By utilizing Inconel grids and reinforced grids, the amount of rod deflection due to electromagnetic forces was minimized and simple support grids were not used.

Table 2-1
Geometric Characteristics of ABB-NV Supplemental Tests

Test No.	Test Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Thimble	GT Diam. ~ in.	Axial Shape	Radial Split Cold/Hot	Shroud Clearance ~ in.
[										]

a, b, c

Table 2-2
Geometric Characteristics of WLOP Correlation and Validation Tests

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Tube	GT Diam. ~ in.	Axial Shape	Radial Split Cold/Hot	Shroud Clearance ~ in.	Minimum Pressure ~ psi	Minimum Flow ~ Mlb/hr-ft^2
						Correlation Data						
[												]
						Validation Data						
[												]

a, b, c

a, b, c

Grid Spacing xxE/yy indicates nominal grid spacing of yy inches with xx inches between last grid and End of Heated Length, EOHL.

Figure 2-1
Radial Geometry – CHF Test Section 190

a, b, c

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Figure 2-2
Axial Geometry – CHF Test Section 190

a, b, c

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Figure 2-3
Radial Geometry – CHF Test Section 175

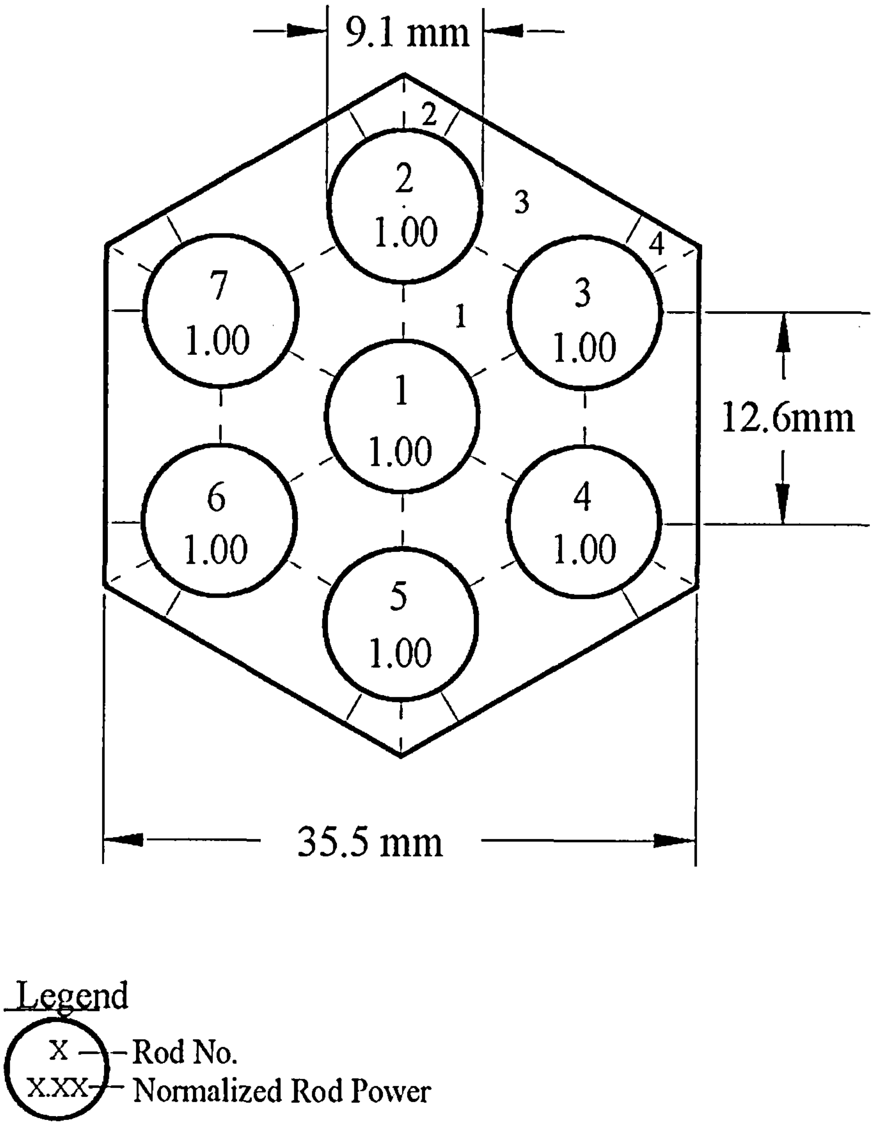

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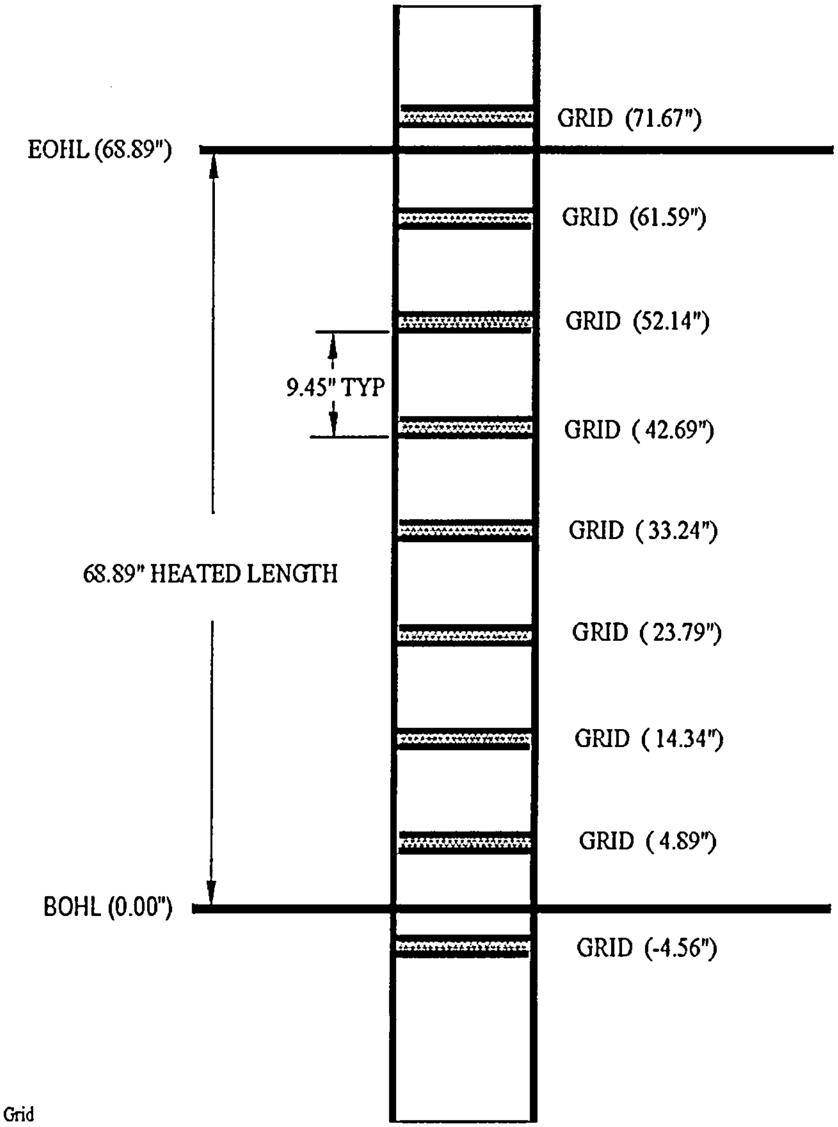
Figure 2-4
Axial Geometry – CHF Test Section 175



Non-Mixing Vane Grid
T/C = Thermocouple
BOHL = Beginning of Heated Length
EOHL = End of Heated Length

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Figure 2-5
Representative Radial Geometry – 14x14 Geometry with "Centered" Thimble

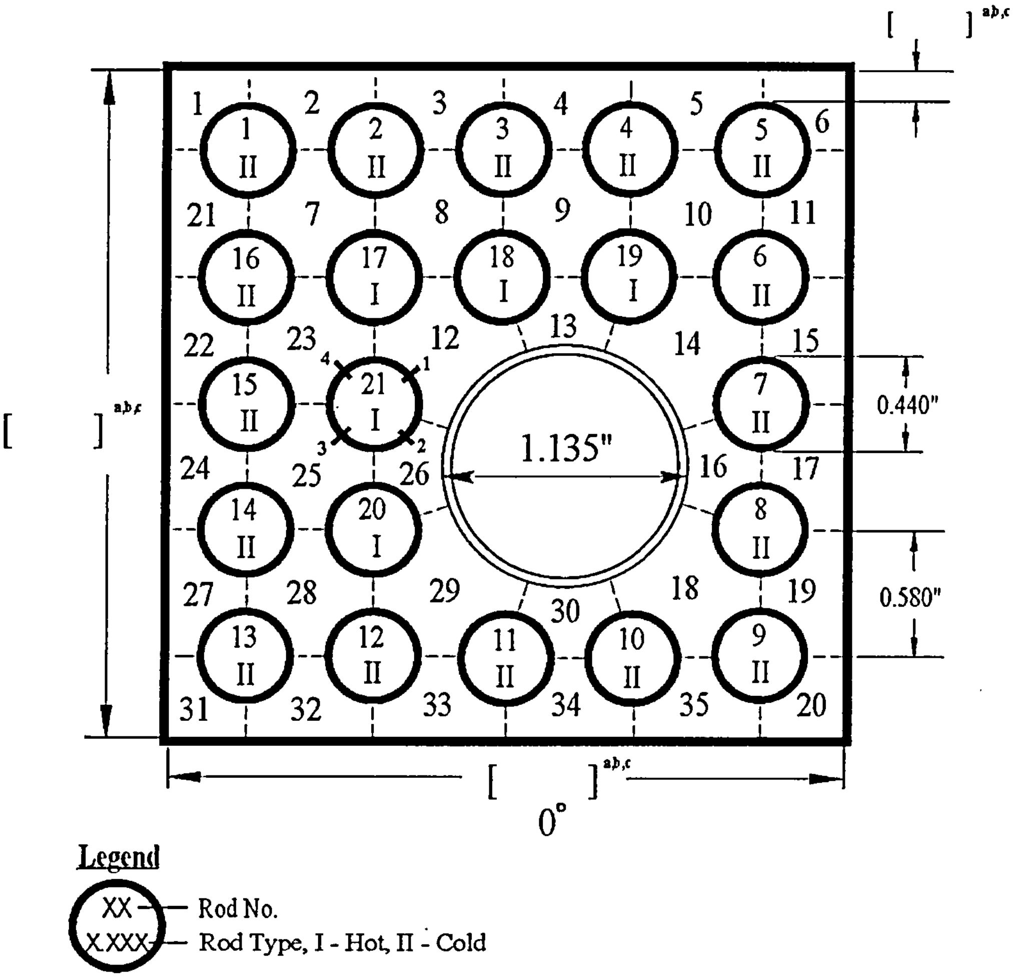

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Figure 2-6
Representative Radial Geometry – 14x14 Geometry with "Offset" Thimble

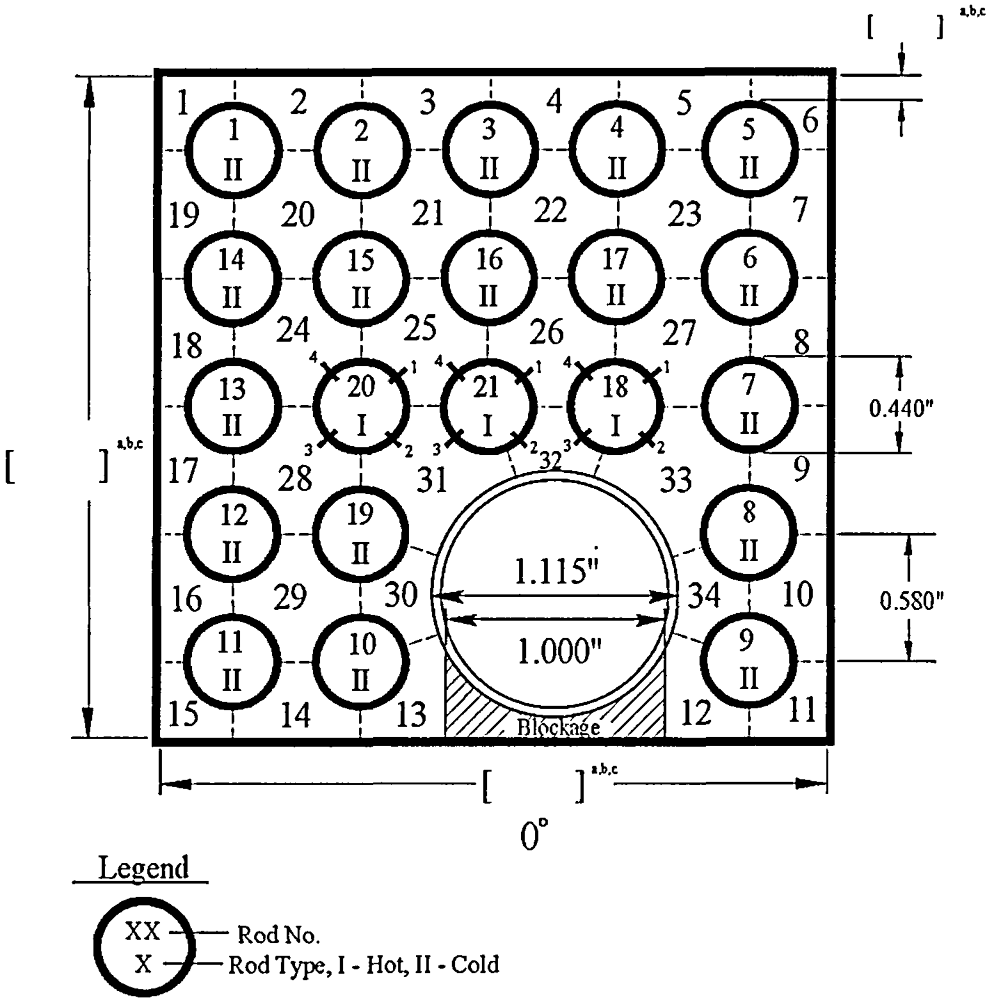

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Figure 2-7
Representative Radial Geometry – 14x14 Geometry without Thimble

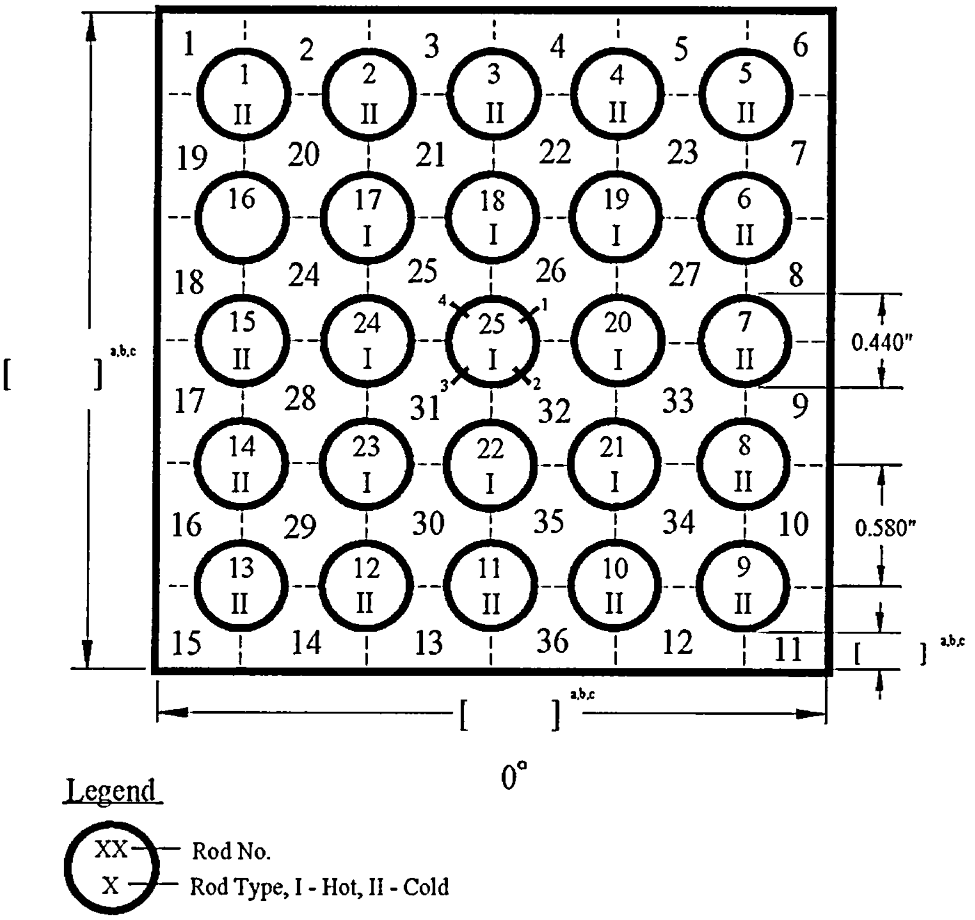

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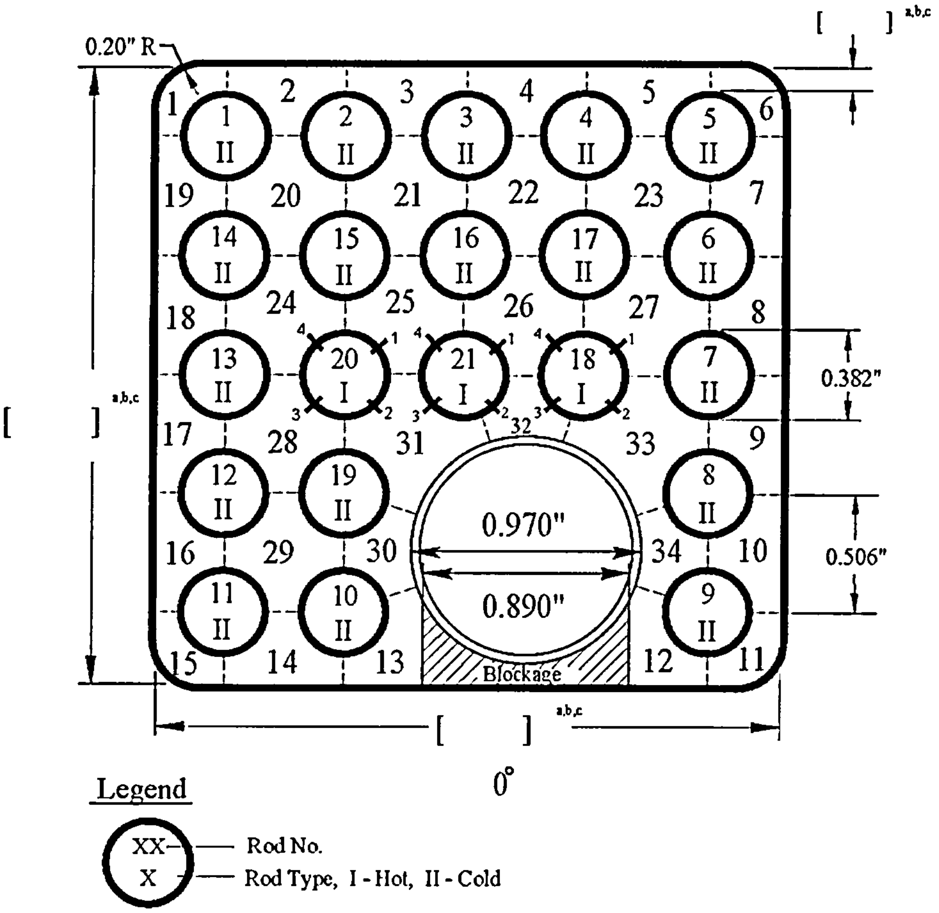
Figure 2-8
Representative Radial Geometry – 16x16 Geometry with "Offset" Thimble



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3.0 Qualification of ABB-NV Correlation for Westinghouse PWR

The ABB-NV database used for correlation development and validation with the VIPRE code for CE-PWR in Reference 3 consists of approximately 720 data points from fourteen test sections in 5x5 arrays simulating CE 14x14 and 16x16 fuel designs with NV grids. The qualification database for the Westinghouse PWR fuel designs consists of approximately 150 additional data points from two new test sections, or approximately 20% of the original database.

3.1 ABB-NV Correlation

The ABB-NV correlation is based on a linear relationship between CHF and local quality. The correlation includes the following variables: pressure, local mass velocity, local equilibrium quality, distance from grid to CHF location, heated length from inlet to CHF location, and heated hydraulic diameter of the subchannel. Special geometry terms are used in the correlation to correct CHF calculations for grid, heated length, heated diameter (cold wall effect) and guide tube effects. The ABB-NV correlation has been used with the TORC code(1) and the VIPRE code(3) for CE-PWR licensing applications. The NRC approved DNBR limit is 1.13 with both codes, from References 3 and 4, at a 95% probability and a 95% confidence level (95/95). A more detailed description of the ABB-NV correlation can be found in Reference 4.

A summary description of the CHF tests supporting the extended application of the ABB-NV correlation for the non-mixing grid region of the Westinghouse PWR is provided in Section 2 of this report. Test 190 used a 5x5 array of electrically heated rods with uniform axial power distribution with brazed Inconel NV grids, which simulated the geometry of a 17x17 fuel design in the reactor assembly. Test 175 was a hexagonal-lattice test with seven rods in a triangular pitch. The test rod dimensions, diameter (0.358 inches) and pitch (0.496 inches), are similar to the Westinghouse PWR fuel design with 0.360-inch rod diameter and 0.496-inch rod pitch. Validation of the ABB-NV correlation to a NV grid test with a different geometry demonstrates that the correlation is robust and is applicable to the NV grid regions of different fuel configurations. Figures showing the geometry for these qualification test sections are also shown in Section 2. The relative radial power split between cold and hot rods ranged from approximately [ ] $^{a, c}$ to 1/1. A summary of the geometric characteristics for the supplemental tests for the ABB-NV database is given in Table 2-1.

3.2 VIPRE Model

A VIPRE model was prepared for each supplemental test section based on the test section axial and radial geometry and test section axial and radial power distributions. Following the VIPRE calculations on the ABB-NV database documented in Reference 3, the VIPRE calculation used the measured values of pressure, inlet temperature, bundle average mass velocity and bundle average heat flux at CHF, as given in Appendix A. The VIPRE turbulent mixing model used for the supplemental tests is the same as that used for the current design applications (3):

w' = [ ] $^{a, c}$

where

[ ] $^{a, c}$

The VIPRE turbulent mixing factor applied was equivalent to the [ ] $^{a, c}$ applied in the VIPRE models for the original ABB-NV original database. The local conditions at the [ ] $^{a, c}$, are used to evaluate the M/P CHF ratio for the qualification database.

VIPRE channel numbering is illustrated in Figures 2-1, 2-3, 2-5 through 2-8. The VIPRE decks are set up with [ ] $^{a, c}$. The grid elevation is specified based on the grid [ ] $^{a, c}$ location. The grid elevations are identified in Section 2. Following the development of the ABB-NV correlation, Reference 4, the [ ] $^{a, c}$ is applied to all channels. It is noted that when [ ] $^{a, c}$ used in the analysis. The use of [ ] $^{a, c}$ is also consistent with the design calculations using the W-3 correlation.

The VIPRE two-phase flow and crossflow correlations are kept the same as that for Westinghouse PWR applications in Reference 2. The input specifications for the VIPRE model are summarized in Table 3-1. The VIPRE/ABB-NV local conditions for the qualification database are listed in Appendix A.

3.3 Data Evaluation and Statistics

The means and standard deviations of the M/P CHF ratios for the qualification database and individual test sections are presented in Table 3-2, along with the data for the original ABB-NV database from Reference 3. The detailed statistical output for the individual test points in the ABB-NV qualification database is provided in Appendix B. It is noted that the ABB-NV correlation predictions are in good agreement with data from tests 190 and 175 even though the distance from grid term, DG, is extended beyond the range of the original database. This demonstrates that the form of the distance from grid term is sufficiently robust to be applicable for slightly larger DG outside the original range. From Appendix B, the values of DG are 21.54 inches for Test 190 and 7.30 inches for test 175. From Reference 4, the form is the distance from grid term is:

[ ] $^{a, c}$

where

DG = Distance from [ ] ^{a,c} to CHF axial location, inches

[ ] ^{a,c}

[ ] ^{a,c}

Further discussion of the statistical evaluation of the ABB-NV correlation, including the qualification database, and the determination of the DNBR 95/95 limit for Westinghouse PWR application is given in Section 5.

Table 3-1

VIPRE Model Input Specifications for Supplemental NV Tests

1. Supplementary DNBRS output file selected: IDNBRS set to 2 or 3 in CONT.6.
2. Single phase friction factor: f = [ ]^{a,b,c}.
3. Two-phase flow Friction multiplier: [ ]^{a,c}.
4. Two Phase Flow: [ ]^{a,c}.
5. Axial nodes: [ ]^{a,c}.
6. Average grid loss coefficient used:
   Test 190 – [ ]^{a,b,c}.
   Test 175 – [ ]^{a,b,c}.
7. The crossflow resistance factor, K: [ ]^{a,b,c}.
   [ ]^{a,b,c}.
8. The turbulent momentum factor: [ ]^{a,b,c}.
9. The traverse momentum parameter: [ ]^{a,b,c}.
10. The axial flow convergence for external iteration, FERROR set to [ ]^{a,b,c}.
11. Turbulent Mixing: [ ]^{a,b,c}.
    This applies to both single and two-phase conditions.
12. Uniform mass velocity was used as the inlet flow option.
13. Radial nodes: Figures 2-1, 2-3, 2-5 through 2-8.

Table 3-2
CHF Test Statistics for ABB-NV Correlation Database with VIPRE Code

a, b, c

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Tube	Axial Shape	N	ABB-NV M/P μ	S

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4.0 Development of Modified ABB-NV Correlation (WLOP) For Low Flow/Low Pressure Conditions

The WLOP correlation was developed based on Critical Heat Flux (CHF) test data obtained from the Heat Transfer Research Facility of Columbia University. The tests were performed with simulated 5x5 arrays of 14x14, 16x16 and 17x17 fuel assembly geometries for non-mixing grids. The correlation database includes tests with uniform and non-uniform radial power distributions, with and without guide thimbles, heated lengths from 48 to 150 inches and grid spacing from 8 to 18.25 inches. To provide overlap with the ABB-NV correlation, the upper pressure of the database is set to be 1800 psia. The lower pressure is determined by the available test data. This limit was chosen since it was found that measured CHF varied with pressure in a more complex manner when the pressure range is increased.

The functional form of the CHF correlation is empirical and is based solely on experimental observations of the relationship between the measured CHF and the correlation variables. The form of the correlation is based on a linear relationship between CHF and local quality similar to the ABB-NV correlation, documented in Reference 4. The WLOP correlation includes the same variables as the ABB-NV correlation: pressure, local mass velocity, local quality, a grid spacing term, heated length from inlet to CHF location and the heated hydraulic diameter ratio of the CHF channel. As discussed in Reference 11, at [ ]^{a,c}. For the NV grids used in this test, this [ ]^{a,c}. To better account for the [ ]^{a,c}, the grid spacing term, GST, is employed in the WLOP correlation. The grid spacing term, GST, is defined as the [ ]^{a,c}. It is noted that for fuel assemblies with [ ]^{a,c}, the grid spacing term, DG, is equally effective as the grid spacing term. The heated hydraulic diameter ratio is defined as the [ ]^{a,c}. Special geometry terms are applied to the correlation to correct CHF for grid spacing, heated length, and heated diameter (cold wall) effects.

4.1 Description of Tests Supporting Correlation

A summary description of the CHF tests supporting the WLOP correlation is provided in Section 2 of this report. A number of the tests used in the development of the ABB-NV correlation in Reference 4 were maintained since they contain data at low flow and low pressure conditions, as well as data to support the geometry terms of the correlation. Included in this group are Tests 18, 21, 36, 38, 47 and 51. Several tests were added to the ABB-NV grid database to provide additional data at the low flow and low pressure conditions. Tests 9, 13, 30, 35 and 39 provided additional data at low flow and low pressure conditions. Tests 10, 19 and 33 were selected to provide grid spacing data. Tests 37 and 42 were selected based upon the amount of available data in the WLOP correlation parameter range for different fuel assembly geometries. Test 190 was selected since it provided the low flow data and simulated the 17x17 fuel assembly geometry.

Similar to the ABB-NV correlation, the WLOP correlation is based upon a series of tests that provide a good representation of the thermal performance of NV grid fuel assemblies. As stated in Appendix C of Reference 8, some early tests for the 14x14 fuel assembly geometry were performed with grids made of Zircaloy-4 and a large clearance, [ ] $^{a, c}$, between the test section shroud and the peripheral heater rods. Later tests were performed with grids made with the stronger Inconel 625 material since some the data obtained with rod bundles using the Zircaloy-4 grids suffered from the effects of larger rod displacements due to electromagnetic attractive forces. The later tests were also run with a tighter shroud clearance, [ ] $^{a, c}$, to reduce the enthalpy difference between the normally colder peripheral subchannels and the hotter interior subchannels and to reduce the excessively large bypass flow. Both of these changes provided a better representation of the thermal performance of fuel assembly in the reactor. Therefore, when available, tests performed with Inconel 625 grids and tighter shroud clearances were chosen for the WLOP and the ABB-NV databases. However, to obtain data at low flow and low pressure conditions, a number of tests with the large clearance, [ ] $^{a, c}$ and Zircaloy grids were selected for the WLOP correlation. The inclusion of the tests with the larger shroud clearance provides conservative estimates of the CHF improvements due to the increased bypass flow in the peripheral subchannels.

To develop a separate validation database for the WLOP correlation, data from three test bundles were selected. These test bundles were similar to tests in the correlation database, and Test 190 provided data for lower mass velocity at the relatively larger grid spacing, 21.46 inches. Test 39 provided low flow and low pressure data for the validation. Test 43 provides validation data for the 16x16 design. The validation data were more than 27% of the total correlation database.

4.2 Modification of ABB-NV Correlation Form

As described in Reference 4, the form of the ABB-NV correlation was initially developed with the primary variables: pressure, local mass velocity, and local quality. Nine terms of the correlation use the primary variables. This [ ] $^{a, c}$ expression is based on a partial expansion of pressure to the second order and local mass velocity and local quality to the first order. This expression can be used to correlate the data from any test section. The correlation form is then adjusted for geometric effects. For the ABB-NV correlation, the geometric parameters include the heated hydraulic diameters of the CHF subchannel, the distance from grid to CHF location, DG, the heated length from beginning of heated length (BOHL) to CHF location, and the proximity of matrix subchannels to large guide tubes in the ABB fuel designs.

From Reference 4, the final ABB-NV correlation form is:

a, c

[ ]

and:

F_{CW} = [ ]^{a,c} Guide thimble heated hydraulic diameter factor
F_{GR} = [ ]^{a,c} Distance from grid factor
F_{HL} = [ ]^{a,c} Heated length factor
F_{GT} = [ ]^{a,c} GT proximity factor

where:

$q''_{CHF,U}$ = Critical Heat Flux based on uniform axial power shapes, MBtu/hr-ft^2
Pr = Pressure, psia
GL = Local mass velocity at CHF, Mlbm/ hr-ft^2
XL = Local coolant quality at CHF, decimal fraction
Dh = Heated diameter of subchannel, inches
Dhm = Heated diameter of matrix subchannel, inches
DG = Distance from [ ]^{a,c} of grid to CHF location, inches
HL = Heated length from beginning of heated length to CHF location, inches
CC = [ ]^{a,c}

Based upon an inspection of the low flow/low pressure data from the correlation database, there are four changes to the ABB-NV correlation form. One change is the addition of a [ ]^{a,c} to the [ ]^{a,c} expression to account for the [ ]^{a,c}. A second change is required to [ ]^{a,c}. The third change is the modification of the grid spacing term, developed in Reference 11 to [ ]^{a,c}. The fourth change is the elimination of the [ ]^{a,c} for matrix subchannels away from a thimble tube. These changes are discussed below. The [ ]^{a,c} are discussed first and then the geometric term multipliers.

4.2.1 Additional Term for Pressure

Following initial correlation efforts with the ABB-NV form, plots of [ ]^{a,c} were generated to understand the [ ]^{a,c}. The data were separated to produce [ ]^{a,c}. It was discovered that the curve consistently [ ]^{a,c} as shown in Figure 4-1. To best fit the data trend, a [ ]^{a,c} expression. The empirical fit to the term was a [ ]^{a,c}. The terms within the [ ]^{a,c} of the correlation then becomes:

a, c

[ ]

4.2.2 Geometry Term Modification

Although both 14x14 and 16x16 data were fit to the ABB-NV correlation without a specific term to account for the [ ]^{a,c}, for low pressure data, there was a [ ]^{a,c}.

This trend is shown in Figure 4-2. To eliminate the trend and to [ ]^{a,c} above. This term is a [ ]^{a,c}. Following this modification, the trend was eliminated, Figure 4-3, and the [ ]^{a,c} in the correlation database were equalized. The terms within the [ ]^{a,c} of the correlation then becomes:

[ ]^{a,c}

4.2.3 Heated Length Term

Following the development of ABB-NV, Test 18 is included in the database along with multiple tests with a heated length of 84 inches and two tests with heated length of 150 inches to determine the coefficients for the [ ]^{a,c} for the heated length term. Since the impact could be somewhat different at low flows and low pressures, new coefficients, B(13) and B(14), are determined from the correlation database. The heated length multiplier has the form:

[ ]^{a,c}

where:

HL = Distance from beginning of heated length (BOHL) to axial location of CHF.

Following the application of ABB-NV, the heated length multiplier is constrained to be constant, HL equals 48 inches, when the heated length is less than 48 inches since there are no CHF data available in this region.

4.2.4 Grid Spacing Term Modification

An [ ]^{a,c} was used in the ABB-NV to correct CHF for different grid spacing. This is adequate when the [ ]^{a,c}. The purpose of this term is to account for the presence of the grid on CHF. This term results in lower CHF just [ ]^{a,c}, which produces better agreement with test results. However, as described in Reference 11, test data with [ ]^{a,c}. This is also true for Tests 9, 10 and 33 in the WLOP database. Test 9 has [ ]^{a,c} to the end of heated length (EOHL). Test 10 has multiple spans with [ ]^{a,c}. Test 33 has a nominal grid spacing of [ ]^{a,c}. From these data, it is concluded that it is more appropriate to use the grid spacing term developed in Reference 11 to provide a more robust form to cover [ ]$^{a, c}$. This is similar to the grid spacing term applied in the WRB-2 correlation, Reference 10. To account for the effect of the [ ]$^{a, c}$, a grid spacing term was developed, defined as:

[ ]$^{a, c}$

where:

[ ]$^{a, c}$

Similar to the distance from grid term in ABB-NV and following Reference 11, the [ ]$^{a, c}$ is shown below:

[ ]$^{a, c}$

4.2.5 Heated Hydraulic Diameter of CHF Subchannel Term

For some fuel assembly designs, there can be a difference in performance for the matrix subchannels near the guide thimble and the guide thimble subchannels. Channel 25 in Figure 2-5 is representative of a matrix subchannel near the guide thimble, channel 26 is representative of the guide thimble side subchannel and channel 12 is representative of the guide thimble corner subchannel. Following the ABB-NV correlation, the heated hydraulic diameter term, or also referred to as the "cold wall" term, is:

[ ]$^{a, c}$

where:

Dhm = Heated hydraulic diameter of a matrix subchannel with the same rod diameter and pitch, inches.
Dh = Heated hydraulic diameter of the subchannel, inches

The range of the test data for the ratio of heated hydraulic diameters is 0.679 – 1.00, so the lower limit for the ratio is set to 0.679.

4.2.6 Proximity of Matrix Subchannel to Guide Tube Multiplier – Modified Term

An examination of the CHF data for the matrix subchannels from the ABB-NV database indicated an improvement in performance in the matrix subchannels for tests without the guide tube compared to data with the guide tube. For the low flow and low pressure conditions, while the same trend is present, the difference in performance is sufficiently small that there is negligible impact on the correlation standard deviation when these terms are dropped. Therefore, this set of terms is not included in the WLOP correlation.

The terms are then combined to produce the final WLOP correlation form:

a, c

[ ]

and:

F_{CW} = [ ]^{a,c} Guide tube heated hydraulic diameter factor
F_{HL} = [ ]^{a,c} Heated length factor
F_{GR} = [ ]^{a,c} Grid Spacing Factor

where:

$q''_{CHF,U}$ = Critical Heat Flux Based on Uniform Axial Power Shapes, MBtu/hr-ft^2
Pr = Pressure, psia
GL = Local Mass Velocity at CHF, Mlb/ hr-ft^2
XL = Local Coolant Quality at CHF, Decimal Fraction
Dh = Heated Diameter of Subchannel, inches
Dhm = Heated Diameter of Matrix Subchannel, inches
DG = Distance from [ ]^{a,c} to CHF Location, inches
GS = Grid Span [ ]^{a,c} of CHF Location, inches
GST = Grid Spacing Term = [ ]^{a,c}
HL = Heated Length From Beginning of Heated Length to CHF Location, Inches

4.3 VIPRE Model

The test data from the Columbia University test facility were evaluated by using the Westinghouse VIPRE thermal hydraulic code$^{(2)}$ in a similar manner used in Reference 3 and in Section 3 of this report for the ABB-NV correlation. The VIPRE code was used to predict local coolant conditions in each subchannel for the CHF test sections at multiple axial nodes based on bundle average data measurements. VIPRE models were prepared for each test section in the database based upon the bundle geometry and the axial and radial power distributions of the test sections, given in Reference 4 or Appendix E. The VIPRE calculations used the measured values of pressure, inlet temperature, bundle average mass velocity and bundle average heat flux, given in Appendix C. The VIPRE turbulent mixing correlation used for the correlation and validation tests can be input as:

w' = [ ]^{a,c}

or

w' = [ ]^{a,c}

where:

w' = Turbulent crossflow velocity, (lbm/sec-ft)

[ ]$^{a, c}$

The VIPRE turbulent mixing factor for the non-mixing grids in the correlation and validation database are equivalent to the [ ]$^{a, c}$ applied in the VIPRE models for the original ABB-NV original database, Reference 4.

VIPRE channel numbering is illustrated in Figures 2-1 and 2-5 through 2-8. The VIPRE decks are set up with [ ]$^{a, c}$ nodes. The [ ]$^{a, c}$ for the grid locations. The grid elevations are identified in Reference 4 or Appendix E. Following the development of the ABB-NV correlation, Reference 4, [ ]$^{a, c}$. It is noted that the code results for the local conditions are [ ]$^{a, c}$ used in the analysis. A summary table of the [ ]$^{a, c}$ for each test is provided in Table 4-1. The VIPRE two-phase flow and cross flow correlations are kept the same as that for Westinghouse PWR applications in Reference 2. The input specifications for the VIPRE model are summarized in Table 4-2.

4.4 Data Evaluation and Statistics

Following the same basic process used to determine the optimum coefficients for ABB-NV in Reference 4, the following steps were performed for the optimization of the WLOP CHF correlation coefficients with the CHF "correlation" database:

1) The data from all the tests in the correlation database are reduced with the VIPRE code to obtain local mass flow and quality conditions for all subchannels and multiple axial nodes for each test run. For the matrix tests, the local conditions from the [ ]$^{a, c}$ from the VIPRE code. For tests with a simulated guide thimble, the local conditions from the [ ]$^{a, c}$ were selected to determine the coefficient for the heated hydraulic diameter ratio term in the correlation form. The [ ]$^{a, c}$ coefficients for the final correlation form were then determined from the [ ]$^{a, c}$ using a non-linear regression analysis. Since these data contained [ ]$^{a, c}$.

2) The data from the correlation database are then reduced with the correlation coefficients determined at the [ ]$^{a, c}$. The data from all the tests in the correlation database are [ ]$^{a, c}$ with the VIPRE code to obtain local mass flow and quality conditions and DNBR calculations for all subchannels and multiple axial nodes for each test run. The local conditions were then [ ]$^{a, c}$ for each test run. While maintaining the heated hydraulic diameter ratio term fixed, the remaining [ ]$^{a, c}$ coefficients of the correlation form were optimized using a non-linear regression analysis.

3) Step 2 was repeated with the WLOP correlation in VIPRE having the coefficients determined in Step 2. The local conditions were then [ ]^{a,c}. The correlation statistics at the [ ]^{a,c} using the coefficients determined in Step 2. The [ ]^{a,c} coefficients were then re-fit using a non-linear regression analysis and the correlation statistics were computed using the new coefficients. Step 3 was repeated until the correlation statistics at the [ ]^{a,c} were unchanged and then the coefficients determined in Step 3 are considered to be final. It is noted that the [ ]^{a,c} coefficients determined from the [ ]^{a,c} with the final form were determined to be the final coefficients.

Following the same process described in Reference 4, a non-linear regression analysis code was also used to sort and fit the test data. The optimization of the constants was performed on data within the following parameter ranges:

System Pressure	Pr	=	180 to 1800 psia
Local Quality	XL	≤	0.750
Local Mass Velocity	GL	=	0.2 to 3.2 Mlbm/ hr-ft^2

For pressure and flow, the limits were set just outside the data range to ensure all data within the above ranges were included. The code was also used to [

]^{a,c}. After the initial runs, the code was also used to separate out outliers, following the procedure described in Section 5. [

]^{a,c}.

The WLOP correlation for low flow and low pressure conditions with the final coefficients for application with the VIPRE code is shown on the following page. The means and standard deviations of the M/P CHF ratios for the correlation database and individual test sections are presented in Table 4-3. As stated earlier, the statistics for the correlation database are based upon the [ ]^{a,c} with the correlation application. The statistical output for the individual test points in the WLOP correlation database are provided in Appendix D. Further discussion of the statistical evaluation of the WLOP correlation is given in Section 5.

Final Correlation Form and Coefficients for WLOP for VIPRE Code

a, b, c

[ ]

The Departure from Nucleate Boiling Ratio (DNBR) is defined as:

$$DNBR = q''_{CHF,U} / q''_{local} * F_C$$

Nomenclature:

$q''_{CHF,U}$ = Critical Heat Flux Based on Uniform Axial Power Shapes, MBtu/hr-ft^2
Pr = Pressure, psia
GL = Local Mass Velocity at CHF, Mlb/ hr-ft^2
XL = Local Coolant Quality at CHF, Decimal Fraction
Dh = Heated Diameter of Subchannel, inches
Dhm = Heated Diameter of Matrix Subchannel, inches
DG = Distance from [ ]^{a,c} to CHF Location, inches
GS = Grid Span [ ]^{a,c} of CHF Location, inches
GST = Grid Spacing Term = [ ]^{a,c}
HL = Heated Length From Beginning of Heated Length to CHF Location, inches
q''_{local} = Local Heat Flux, MBtu/hr-ft^2
F_C = F-Factor To Correct $q''_{CHF,U}$ For Non-uniform Axial Power Shapes, specified in Section 6 in description of applications

4.5 Validation of Correlation

An independent validation database was generated from data excluded from the database for correlation development to verify performance of the WLOP correlation, as described in Section 4.1. The geometric characteristics for these tests are summarized in Table 2-2. The validation database was generated in a manner similar to the process used to generate the correlation database [ ]^{a,c}.

A VIPRE model was prepared for each validation test section based on the bundle geometry and the axial and radial power distributions. The VIPRE calculation used the measured values of pressure, inlet temperature, bundle average mass velocity and bundle average heat flux at CHF, as given in Appendix C.

The local conditions at the [ ] [a, c], are used to evaluate the M/P CHF ratio.

The means and standard deviations for the M/P CHF ratio for the validation database and individual test sections are presented in Table 4-3, along with the correlation database. The statistical output for the individual test points in the WLOP validation database is provided in Appendix D. Further discussion of the statistical evaluation of the WLOP correlation is given in Section 5.

4.6 Demonstration Test Results

Special demonstration tests were run using available data for MV grid designs to demonstrate that the WLOP correlation is applicable or conservative for application with mixing vane grid designs. In general, MV grids have shown substantial performance gains when compared to non-mixing vane grids, especially at small grid spacing, Reference 4. Also, as identified in Reference 11, mixing vane grids have demonstrated a [ ] [a, c], as for WLOP. A summary description of the Mixing Vane CHF tests supporting the application of the WLOP correlation to mixing vane grid designs is provided in Table 4-4. It is noted that many of these tests are the same tests used to develop and support previous correlations, such as the ABB-X2, WRB-1, WRB-2 and WRB-2M correlations, References 9 through 12.

VIPRE models were prepared for each test section in the database based upon the bundle geometry and the axial and radial power distributions, References 9, 11 and 12. The [ ] [a, c]. An [ ] [a, c] to be consistent with the development of the WLOP correlation. The local conditions at the [ ] [a, c], are used to evaluate the M/P CHF ratio.

The results, given in Table 4-5, confirm that WLOP predictions are conservative when applied to the MV grid data. It is noted that there is fairly large scatter due to the [ ] [a, c]. Plots of the WLOP correlation M/P versus pressure and flow, Figures 4-4 and 4-5 indicate that WLOP M/P values [ ] [a, c]. Since the data with [ ] [a, c], the data from Test 96 are not shown in Figures 4-4 and 4-5. Thus, the mixing vane data for a [ ] [a, c].

Table 4-1
[ ]^{a,c} Loss Coefficients Input to VIPRE
[ ]^{a,c}

a, b, c

Table 4-2
VIPRE Model Input Specifications for WLOP Tests

1. Supplementary DNBRS output file selected: IDNBRS set to 2 or 3 in CONT.6
2. Single phase friction factor f = [ ]^{a,b,c}
3. Two-phase flow Friction multiplier: [ ]^{a,c}
4. Two Phase Flow: [ ]^{a,c}
5. Radial nodes: Figures 2-1, 2-5 through 2-8
6. Loss coefficient used: See Table 4-1
7. The crossflow resistance factor, [ ]^{a,b,c}
   [ ]^{a,b,c}
8. The turbulent momentum factor: [ ]^{a,b,c}
9. The traverse momentum parameter [ ]^{a,c}
10. The axial flow convergence for external iteration, FERROR set to [ ]^{a,b,c}
11. Turbulent Mixing: [
    ]^{a,b,c}

    For Demonstration Tests [ ]^{a,c}
    This applies to both single and two-phase conditions
12. Uniform mass velocity was used as the inlet flow option
13. [ ]^{a,c} for non-uniform tests

/

Table 4-3
CHF Test Statistics for WLOP Correlation/Validation Database with VIPRE Code

a, b, c

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Thimble	Axial Shape	N	WLOP M/P μ	S
Correlation Data										

Notes:

N	- Number of Data Points
μ	- Mean of Measured over WLOP Predicted CHF, M/P
S	- Standard Deviation of M/P

Table 4-4
Geometric Characteristics of the WLOP Mixing Vane Demonstration Tests

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Thimble	GT Diam. ~ in.	Axial Shape	Radial Split Cold/Hot	Shroud Clearance ~ in.	Minimum Pressure ~ psi	Minimum Flow ~ Mlb/hr-ft^2
Demonstration Data												

a, b, c

Grid Spacing xxE/yy indicates nominal grid spacing of yy inches with xx inches between last grid and End of Heated Length, EOHL.

Table 4-5
CHF Test Statistics for WLOP Correlation in VIPRE Code for Mixing Vane Tests

Test No.	Rod Diam. ~ in.	Rod Pitch ~ in.	Dhm ~ in.	Heated Length ~ in.	Grid Spacing ~ in	Axial Shape	Guide Thimble	WLOP	
								N	M/P Mean, μ

a, b, c

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Figure 4-1
Measured CHF Versus Pressure

a, b, c

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Figure 4-2
Trend of Initial M/P with Flow

a, b, c

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Figure 4-3
Trend of M/P with Flow
Based on Final Correlation Form

a, b, c

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Figure 4-4

Trend of M/P with Pressure for Demonstration Mixing Vane Data

a, b, c

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Figure 4-5
Trend of M/P with Flow for Demonstration Mixing Vane Data

a, b, c

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5.0 Statistical Evaluation

The mean and standard deviation for the ratio of measured to ABB-NV predicted CHF with the VIPRE code are given in Table 3-2 for the original and Westinghouse PWR supplemental qualification database. To determine the one-sided 95/95 DNBR limit applicable to the application of the ABB-NV correlation to the NV grid region of Westinghouse PWR fuel designs, a statistical evaluation is performed with the ABB-NV correlation on the original and qualification databases to determine poolability. Statistical evaluations are then performed on [ ] $^{a, c}$, following Reference 4, to determine the one-sided 95/95 DNBR limit for the application of the ABB-NV correlation for Westinghouse PWR fuel designs. The statistical tests applied are the same tests applied in Reference 4 for the ABB-NV correlation. It is noted that no points in the Westinghouse PWR qualification database were eliminated as outliers per the procedure given in Chapter 17 of Reference 12, a rigorous outlier test applied in Reference 4. Tests for normality at the 95% confidence level were performed on the above data sets to determine the proper statistical methods to be used for the data. The W and D' tests(13) were used to evaluate normality of each test in the supplemental database [ ] $^{a, c}$. Normality tests for the original database are documented in Reference 4. The W test is applied to tests with less than 50 test points and the D' test is applied to all other test groups.

For the modified ABB-NV correlation for low flow and low pressure conditions, WLOP, the mean and standard deviation for the ratio of measured to WLOP predicted CHF are shown in Table 4-3 for the correlation and validation databases and the individual test sections. Following the procedure used in Reference 4, a statistical evaluation is performed with the WLOP correlation for [ ] $^{a, c}$, the correlation database, the validation database and a combined correlation and validation database to determine the applicable one-sided 95/95 DNBR limit. Based upon the results of the outlier test, described in 5.1.1, [ ] $^{a, c}$ were eliminated as outliers per the procedure given in Chapter 17 of Reference 12. These points had measured to predicted CHF ratios, M/P, [ ] $^{a, c}$. Tests for normality at the 95% confidence level were performed on the above data sets to determine the proper statistical methods to be used for the data. Since some individual tests had less than 50 points, the W and D' tests, Reference 13, were used to evaluate normality.

Statistical tests were then performed to determine if all or selected data groups belong to the same population, in order to be combined for the evaluation of the 95/95 DNBR tolerance limit for the ABB-NV correlation for Westinghouse PWR application and the WLOP for both CE-PWR and Westinghouse PWR application. For normally distributed groups, homogeneity of variance was examined using Bartlett's test, Reference 14. Homogeneity of the means was then examined with the t-test or general F-test. The t-test with equal variances, Reference 15, was applied for testing the equality of means of two groups that passed both the normality tests and the homogeneity of variance test. The t-test with unequal variances, Reference 16, was applied for testing the equality of means of two groups that passed the normality tests but failed the homogeneity of variance test. The ANOVA F-test was applied to multiple groups that passed the normality tests. For groups that did not pass the normality test, the Wilcoxon-Mann-Whitney test or the Kruskal-Wallis One-Way Analysis of Variance by Ranks test, References 15 and 20, is used to test the null hypotheses that the medians, or averages, of the tests or groups are the same. The Wilcoxon-Mann-Whitney test was applied for testing whether two groups could have been drawn from the same population and the Kruskal-Wallis One-Way Analysis of Variance by Ranks test was applied to multiple groups. Since the groups that failed the D' normality test passed other normality tests, such as the Kolmogorov-Smirnov test, the Bartlett and F-tests were initially applied to check for poolability of these groups. Data that did not pass any of these tests were not combined.

Since it is proper to utilize all data in the evaluation of the correlation, as was done in Reference 4, the one-sided 95/95 DNBR tolerance limit is calculated for a combined ABB-NV original database and the ABB-NV supplemental qualification database for Westinghouse PWR fuel designs, if the data are poolable, or for the [ ]^{a,c} if not all of the tests are poolable. The same approach is applied to the WLOP correlation and validation databases. For normally distributed groups, Owen's one-sided tolerance limit factor(18) is used to compute the 95/95 DNBR limit. For groups that are not normally distributed, a distribution-free or non-parametric limit, from Chapter 2 of Reference 12, is established. To cover all regions with the 95/95 limit, the most conservative limit for [ ]^{a,c} is applied to the entire set of data.

Scatter plots were then generated for each of the variables in each correlation to examine the correlation for trends or regions of non-conservatism. The measured to correlation predicted CHF ratio is plotted as a function of pressure, local mass velocity, local quality, heated hydraulic diameter ratio, [ ]^{a,c}, the matrix hydraulic diameter, the heated length form BOHL to location of CHF and the grid spacing term. For the extension of ABB-NV to Westinghouse PWR fuel designs, the qualification data were plotted separately from the original data, although data could be pooled, for information. The DNBR limit is also shown on these plots to show the number of test points that fall below the limit and the location of those points. The total number of test points that fall below the limit is also identified.

5.1 Statistical Tests

5.1.1 Treatment of Outliers

Each database is examined for outliers by the following method:

The probability of rejecting an observation when all data belong to the same group, α, was selected to be 0.05. The term $\alpha' = 1 - (1-\alpha)^{1/n}$ is computed. The value of $(1 - \alpha'/2)$ is the normal cumulative distribution value, P, and the value of $z_{1-\alpha'/2}$ is calculated or taken from cumulative normal distribution tables. For a mean value of m, the values of a and b are computed where:

$$a = m - \sigma * z_{1-\alpha'/2}$$
$$b = m + \sigma * z_{1-\alpha'/2}$$

Any observation that does not lie in the interval a to b is rejected. The method does assume a normal distribution and the values of μ, mean of the data, and s, standard deviation of the data, are reasonable estimates of m and σ. Therefore, care must be taken to ensure the elimination of outliers is justifiable. Based upon this evaluation, no points in the Westinghouse PWR qualification database in Section 3 were eliminated for the ABB-NV correlation extension. Based upon this evaluation, [ ]^{a,c} in Section 4 were eliminated. [ ]^{a,c} had measured to predicted CHF ratios, M/P, [ ]^{a,c}.

5.1.2 Normality Tests

The W and D' tests, Reference 13, were used to evaluate the assumption of a normal distribution. For individual tests with less than 50 test points, the W test is applied. The test statistic W is computed as:

$$W = b^2 / S^2$$

where:

$$S^2 = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

$$b = \sum_{i=1}^{k} a_{n-i+1} (x_{n-i+1} - x_i) \qquad x_i \textit{ in ascending order}$$

a_i from Table 1, Reference 13
k = n/2 if n is even and k = (n-1)/2 if n is odd

The value of W is compared with percentage points of the distribution of W for P set to 0.05 from Table 2 of Reference 13. Small values of W indicate non-normality. For combined tests or individual tests with $n \geq 50$, the D' normality test is applied. The test statistic D' is computed as:

$$D' = T / S$$

where:

$$S = \left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{0.5}$$

$$T = \sum_{i=1}^{n} \{i - (n+1)/2\} x_i \qquad x_i \textit{ in ascending order}$$

The calculated value of D' is compared with the percentage points values of the distribution of D' from Reference 13. The D' test indicates non-normality if the calculated value of D' falls outside of the range established from Reference 13 for P set to 0.025 and 0.975. These tests were selected since they are considered to be more rigorous compared to other normality tests such as the Kolmogorov-Smirnov test.

Furthermore, the D' and W tests are the ANSI standard tests that have been used in previous data analyses reviewed and approved by the NRC.

5.1.3 Statistical Tests for Comparison of Data Groups

Statistical tests were performed to determine whether data groups could be considered to come from one population. The Bartlett test for homogeneity of variances and the t-test, for 2 groups, or the F-test, for multiple groups are applied to determine if data groups can be combined. If the data groups fail the normality test or the homogeneity of variances test, the Mann-Whitney Rank Sum test or the Kruskal-Wallis One-Way Analysis of Variance by Ranks test is used to check the null hypotheses that the medians, or averages, of the tests or groups are the same. For the groups that pass the equality of means tests or the non-parametric tests for the null hypothesis that the samples are from the same population, the normality tests are applied to the combined groups to check the assumption of normality. If the combined group passes the normality test, Owen's one-sided tolerance limit factor(18) is used to compute the 95/95 DNBR limit. If the combined group fails the normality test, a distribution-free one-sided 95/95 limit is determined, Chapter 2 of Reference 12. A brief description of the comparison tests is given below:

5.1.3.1 Homogeneity of Variances

One of the most used tests for examining the homogeneity of a set of variances is Bartlett's test(14). Bartlett showed that for a set of variances estimated from K independent samples from normal distributions having a common variance σ^2, a quantity M/C would have a distribution satisfactorily approximated by the χ^2 distribution. Specifically:

$$M = N \ln \left\{ N^{-1} * \sum_{t=1}^{K} \nu_t s_t^2 \right\} - \sum_{t=1}^{K} \nu_t \ln s_t^2$$

$$C = 1 + \frac{1}{3\,(K-1)} \left\{ \sum_{t=1}^{K} \frac{1}{\nu_t} - \frac{1}{N} \right\}$$

where:

s_t^2 Is an estimate of variance for test section t based on degrees of freedom ν_t,

K is the number of test sections,

$N = \sum_{t=1}^{K} \nu_t$

and the quantity M/C is distributed approximately as χ^2 with K-1 degrees of freedom.

5.1.3.2 Test for Equality of Means for Two Data Groups - Unpaired t-Test

When data from two groups passed the test for homogeneity of variances, the t-Test was employed to test the hypothesis that $\mu_1 - \mu_2 = 0.0$ or that $\mu_1 = \mu_2$, where μ_1 is the mean from data group 1 and μ_2 is the mean from data group 2. The test statistic t is calculated with the expression:

$$t = \frac{\mu_1 - \mu_2}{s_o\left(\frac{1}{n1} + \frac{1}{n2}\right)^{0.5}}$$

where:

$$s_o^2 = \frac{\sum_{j=1}^{n1}(x_{1j} - \mu_1)^2 + \sum_{j=1}^{n2}(x_{2j} - \mu_2)^2}{n1 + n2 - 2}$$ is a “pooled” estimate

The computed value of t is compared with the value $t_{\alpha/2,\, n1+n2-2}$ in a table of percentiles of the t distribution for α set to 0.05. The hypothesis that $\mu_1 = \mu_2$ is rejected, if the computed value of t is larger then the value of $t_{\alpha/2,\, n1+n2-2}$.

When data from two groups passed the test for normality, but not the test for homogeneity of variances, a t-Test with unequal variances described below was employed to test the hypothesis that $\mu_1 - \mu_2 = 0.0$ or that $\mu_1 = \mu_2$ where μ_1 is the mean from data group 1 and μ_2 is the mean from data group 2. From Reference 16, the test statistic t is calculated with the expression:

$$t = \frac{\mu_1 - \mu_2}{\left(\frac{S_1^2}{n1} + \frac{S_2^2}{n2}\right)^{0.5}}$$

where:

S_i^2 - Variance of sample i
ni - Number of Data, sample i

5.1.3.3 Test for Equality of Means for Multiple Data Groups – Analysis of Variance, F-Test

An analysis of variance test was performed to test the equality of means and determine whether the data from multiple tests or groups could be pooled. One of the usual techniques for examining the equality of means determined in an experimental study is a particular form of the F-test. In this technique, two mean squares are found, call them S_1, the between test section mean square and S_2, the within test section mean square. If K is the number of test sections, n_t the number of data for test section t and n is the total number of data,

$$S_1 = \frac{\sum_{t=1}^{K} n_t\left(\overline{X}_t - \overline{\overline{X}}\right)^2}{K - 1}$$, and

$$S_2 = \frac{\sum_{t=1}^{K}\left\{\sum_{i=1}^{n_t}\left(X_{ti}-\overline{X}_t\right)^2\right\}}{n-K}$$

In these expressions X_{ti} is an individual datum for test section t, $\overline{X}_t$ is the mean value of X for test section t and $\overline{\overline{X}}$ is the grand mean for all data. Under the hypotheses of normality, homogeneity of variance and equality of means, S_1 and S_2 are independent estimates of the variance, σ^2, due to random deviation from the true grand mean. Therefore the ratio:

$F = S_1 / S_2$ should follow the F distribution with degrees of freedom,
$\nu_1 = K-1$ and $\nu_2 = n-K$.

The calculated value of F is compared with the value of $F_{1-\alpha}(\nu_1, \nu_2)$ for α set to 0.05. Should the test section means not be equal, S_1 will contain additional components of variance. Therefore, large values of F require the rejection of the hypothesis of equality among the means of the tests or groups.

5.1.3.4 Distribution Free Comparison of Average Performance

For combinations that have one or both tests fail the normality test, the Wilcoxon-Mann-Whitney Test(12)(17) is used to compare two groups. To apply this test when one of the samples has n > 10, all groups considered, the data are combined. The number of points in the smaller sample is m; the number from the larger group is n. The M/P CHF values from the two groups are ranked from 1 to m+n = N with tied ranks being assigned the average. The value of T is computed by summing the ranks in the smaller group. The value of z is then computed with the expression:

$$z = \frac{T \pm 0.5 - m*(N+1)/2}{\left[m*n*(N+1)/12\right]^{0.5}}$$

The significance of z is assessed from cumulative normal distribution table. The value of z must fall between -1.645 to +1.645 for the two groups to pass the null hypotheses that the groups are drawn from the same population for P equal 0.950 for the left and right tails of the distribution.

For comparison of tests or multiple groups that failed the Bartlett test for equal variance or the D' test for normality, the Kruskal-Wallis One-Way Analysis of Variance by Ranks test(12)(17) is used. The level of significance of the test, α, is selected to be 0.05. The $\chi^2_{1-\alpha}$ value for K-1 = degrees of freedom is taken from a table of the percentiles of the χ^2 distribution. The data from all tests or groups are ranked from lowest to highest. The H statistic is then calculated with the equation:

$$H = \frac{12}{N(N+1)} * \sum_{i=1}^{K} \frac{R_i^2}{n_i} - 3*(N-1)$$

where R_i is the sum of the ranks for the ith test, n_i is the number of points in test i and N is the total number of points. If $H > \chi^2_{1-\alpha}$, one rejects the hypothesis that the averages are the same.

5.1.4 One-sided 95/95 DNBR Limit

All data from the correlation and validation databases could be considered in the establishment of the one-sided 95/95 DNBR tolerance limit if the data can be pooled. Therefore, the comparison tests are performed on the combined data sets prior to the determination of the 95/95 DNBR limit. If not all of the data passed the analysis of variance tests, the data were grouped into [
]^{a,c} and the 95/95 DNBR limit was established for the different groups of pooled data. The computed 95/95 DNBR limit for the class of data provides 95% probability at the 95% confidence level that a rod in that class having that DNBR will not experience CHF. The most conservative limit determined for any group of data examined is then applied to the entire correlation data set. For normally distributed groups, Owen's one-sided tolerance limit factor$^{(18)}$ is used to compute the 95/95 DNBR limit. For groups that are not normally distributed, a distribution-free or non-parametric limit, from Chapter 2 of Reference 12, is established.

5.1.4.1 Normally Distributed 95/95 DNBR Limit

The mean and standard deviation of the ratio of measured to predicted CHF are computed for each data group or class of data that pass the comparison tests and D' normality test. This group can include all data from the correlation database and validation database or a subset of that data. A 95/95 DNBR limit is evaluated for each group based on the following formulas:

$$DNBR_{95/95} = \frac{1}{\overline{X} - KS}$$

$$K = \frac{1.645 + 1.645\left[1-\left(1 - \frac{2.706}{2(n-1)}\right)\bullet\left(1 - \frac{1}{n}\right)\right]^{\frac{1}{2}}}{1 - \frac{2.706}{2(n-1)}}$$

where:

$\overline{X}$ = mean of ratio of measured to predicted CHF
S = standard deviation of measured to predicted CHF
K = 95/95 confidence multiplier (Expression given in Reference 18, practically equivalent to Owen's tables in Reference 21)
n = number of data points

5.1.4.2 Distribution Free 95/95 Limit

For data groups that do not pass the D' normality test, a distribution free one-sided 95/95 limit is established. Table A-31 of Reference 12 gives the largest value of m such that one can assert with 95% confidence that 95% of the population lies above the mth smallest value of X_i where X_i is an individual test run value of the ratio of measured to correlation predicted CHF in the non-normally distributed group.

As stated earlier, if all of the data in the combined correlation and validation database could not be pooled, the most conservative 95/95 limit for any subset of that data is the specified limit for the correlation. As a check on the limit, the total number and percentage of test points that fall below the specified limit are also identified. In addition, the limit computed for the entire database is computed using the total variance approach applied in References 10 and 11. Also, the limit for the entire database is computed using the distribution free method if the entire database is not normally distributed.

5.1.5 Graphical Verification

After the determination of the 95/95 DNBR limit for the correlation, scatter plots are then generated for each of the variables in the correlation to examine the correlation for trends or regions of non-conservatism. The measured to correlation predicted CHF ratio is plotted as a function of pressure, local mass velocity, local quality, heated hydraulic diameter ratio, [ ] $^{a, c}$, the matrix hydraulic diameter, the heated length form BOHL to location of CHF and the grid spacing term. The DNBR limit is also shown on these plots to show the number of test points that fall below the limit and the location of those points. The total number of test points that fall below the limit is also identified.

5.2 ABB-NV Correlation Statistical Evaluation and 95/95 DNBR Limit for Westinghouse PWR Application

The D' normality tests and comparison tests were performed to determine if the ABB-NV original data and qualification data were random samples from one or more populations and whether the data from individual tests and the combination of tests were normally distributed. As stated in Section 5.0, parametric comparison tests were performed to determine if data from the different test sections were poolable, then normality tests were performed on the pooled data. If the pooled data failed the normality test, non-parametric tests were performed to check the hypothesis that the averages for the pooled tests are the same. The data were examined in the following order:

1.) [ ] $^{a, c}$. The mean and standard deviation for the ratio of measured to ABB-NV predicted CHF are shown in Table 3-2 for the original database and the qualification database. The original database has 718 points and the qualification database has 147 points or 17% of the total points within the range of applicability. The original database did not pass the D' normality test, so the Wilcoxon-Mann-Whitney test was applied for testing the poolability of the two groups. It is noted that the qualification database did pass the D' normality test. [

]^{a,c}. The results from the tests are summarized in Table 5.2-1. Although the [ ]^{a,c} are also given in Table 5.2-1. Based on these comparisons, the qualification database for the 17x17 designs can be pooled with the original database for the 14x14 and 16x16 fuel designs to determine the 95/95 DNBR limit.

2.) Since no bias is observed between the original database and qualification database due to bundle array geometry, a multiple data analysis was performed on all of the test section data following Reference 4, [ ]^{a,c}. The results of the parametric comparison tests are given in Table 5.2-2. Based upon these results, it is concluded that [

]^{a,c}. Following Reference 4, [

]^{a,c}, are identified below:

a, b, c

Subset	Tests Included	No. Points	Mean	Std. Dev.

As stated in Reference 4, since [

]^{a,c} are given in Table 5.2-3.

3.) The W and D' normality tests were then applied to the data from each test section and each set of data, as shown in Table 5.2-4. The data for the original database are taken from Reference 3.

4.) The one-sided 95/95 DNBR tolerance limit for the limiting subsets is provided in Table 5.2-5. Based upon the data presented in this table, [ ]^{a,c}, the DNBR limit [ ]^{a,c} is 1.1325. [ ]^{a,c}, using the Owen's one-sided tolerance factor.

Based on this evaluation, it is concluded that the DNBR limit of 1.13 is applicable for the entire database. A plot of the measured CHF versus the ABB-NV predicted CHF for all the test data is given in Figure 5.2-1, along with the DNBR limit curve. The DNBR limit of 1.13 is equivalent to a value of 0.885 for the M/P CHF ratio. It is noted that for the entire database, twenty-six test points, or 2.6% of the data fall below the $M/P_{95/95}$ limit of 0.885. [

]^{a,c}.

The data are then examined graphically in order to check for any deviation as a function of the correlation variables. The plots of the M/P CHF ratio as a function of pressure, local mass velocity, local quality, heated hydraulic diameter ratio, matrix heated hydraulic diameter, Dhm, heated length from BOHL to location of CHF, HL, and distance from bottom of adjacent upstream grid, DG, are shown in Figures 5.2-2 through 5.2-8. The DNBR limit is also shown on these plots to show the number of test points that fall below the limit and the location of those points. For information, the original data and qualification data are identified in the plots even though the data were combined in the determination of the one-sided DNBR limit. There are no significant observed adverse trends on any of the plots.

It is also noted that for the Westinghouse PWR geometry, the non-mixing vane region is well below the minimum heated length of 48 inches. Therefore, there is conservatism in the application of the ABB-NV correlation to this region. In addition, the test with a bottom peak non-uniform shape, Test 60, [ ]$^{a, c(3)}$. Based upon the results and the identified conservatism's, it is felt that the 95/95 DNBR limit of 1.13 is conservative to this region for Westinghouse PWR fuel designs. The parameter ranges for the combined database with the ABB-NV correlation are given in Table 5.2-6.

Table 5.2-1
ABB-NV Original and Qualification Database Comparison Tests

Bartlett Test Results - ABB-NV Data

Database	N	Mean	s	K	M	C	M/C	$\chi^2_{.95}$	Pass Test

a, b, c

Wilcoxon-Mann-Whitney Rank Sum Test Results - ABB-NV Data

Database	N	Median	T	m	n	z	$z_{0.95}$	Pass Test

a, b, c

t-Test Results with Unequal Variances - ABB-NV Data

Database	N	Mean	s	$\mu1 - \mu2$	$s_{\bar{x}}$	t	$t_{.975}$	Pass Test

a, b, c

Table 5.2-2

Statistical Comparison Tests

Combined ABB-NV Original and Qualification Database

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Tube	Axial Shape	N	ABB-NV M/P μ	S

a, b, c

Bartlett Test Results - ABB-NV Data Individual Tests

Database	N	Mean, μ	s	K	M	C	M/C	$\chi^2_{.95}$	Pass Test
ALL	865	1.0115	0.0671	16	56.984	1.0071	56.584	25	No

Kruskal-Wallis Variance By Ranks Test Results - ABB-NV Data Individual Tests

Database	N	Mean, μ	s	K	H	$\chi^2_{.95}$	Pass Test
ALL	865	1.0115	0.0671	16	195.29	25.000	No

Table 5.2-3
Comparison Tests for Pooled Subsets
Combined ABB-NV Original and Qualification Database

Bartlett Test Results - ABB-NV Combined Original and Qualification Data

Database	N	Mean, μ	s	K	M	C	M/C	$\chi^2_{.95}$	Pass Test

a, b, c

[ ]

F-Test Results – ABB-NV Data

Database	n_1	n_2	S_1	S_2	S_1 / S_2	$F_{.95}(n_1, n_2)$	Pass Test

a, b, c

[ ]

Kruskal-Wallis Variance By Ranks Test Results - [ ]^{a,c}

Database	K	H	$\gamma^2_{.95}$	Pass Test

a, b, c

[ ]

[ ]^{a,c}

[ ]^{a,c}

Table 5.2-4
D' Normality Tests – ABB-NV Original and Qualification Data Combined ABB-NV Original and Qualification Database

D' Normality Tests – ABB-NV Data Original and Qualification Database

Data	N	Mean	D' Calculated	D' P=.025	D' P=.975	Pass Test

a, b, c

[ ] a, c
[ ] a, c

* Original VIPRE Data taken from Reference 3

Table 5.2-5
Determination of 95/95 DNBR Limit for Pooled Data
Combined ABB-NV Original and Qualification Database

Calculation of $DNBR_{95}$ Limit Calculation for Parametric Data

Database	Mean. μ	s	n	K	$DNBR_{95}$

[ ]a, b, c

Calculation of $DNBR_{95}$ Limit Calculation for Non-parametric Data

Database	γ	P	n	m	M/P = Value	1/Value = $DNBR_{95}$

[ ]a, b, c

Ranking of Data [ ]a, b, c

[ ]a, b, c

Table 5.2-6
Parameter Range for Extension of ABB-NV Correlation Combined ABB-NV Original and Qualification Database

Parameter	Minimum	Maximum
Pressure (psia)	1740	2415
Local Coolant Quality	-0.16	0.22
Local Mass velocity (Mlbm/hr-ft^2)	0.84	3.12
Heated Hydraulic Diameter Ratio, [ ]^{a,c}	0.679	1.08
Heated Length, HL (inches)	48	150
Distance From Grid, DG (inches)	7.3	22

Figure 5.2-1
Measured versus VIPRE/ABB-NV Predicted Critical Heat Fluxes

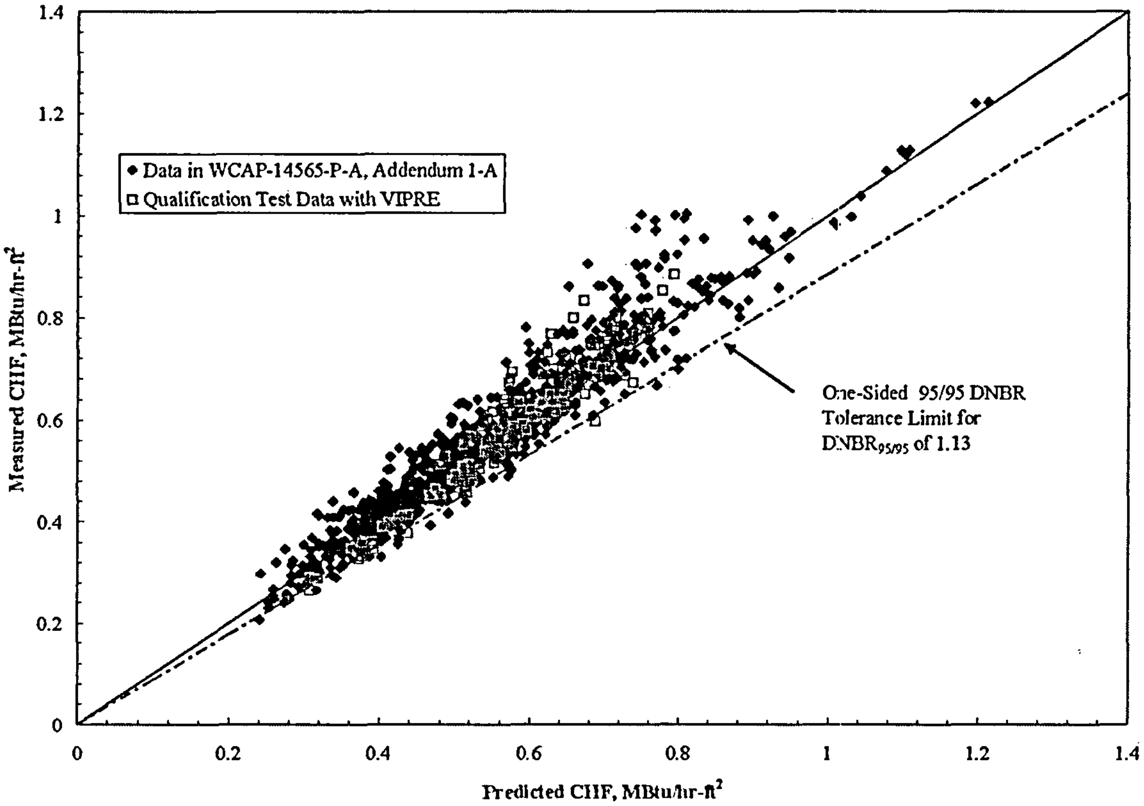

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Figure 5.2-2
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Pressure

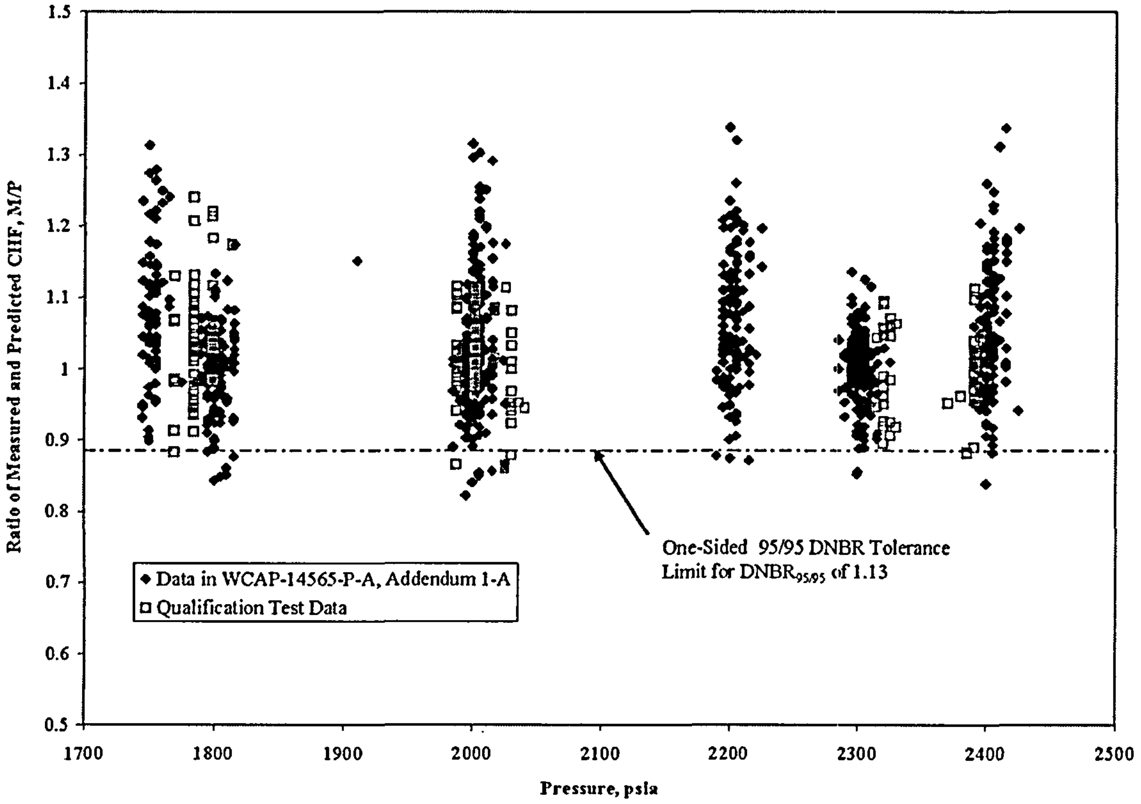

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Figure 5.2-3
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Local Mass Velocity

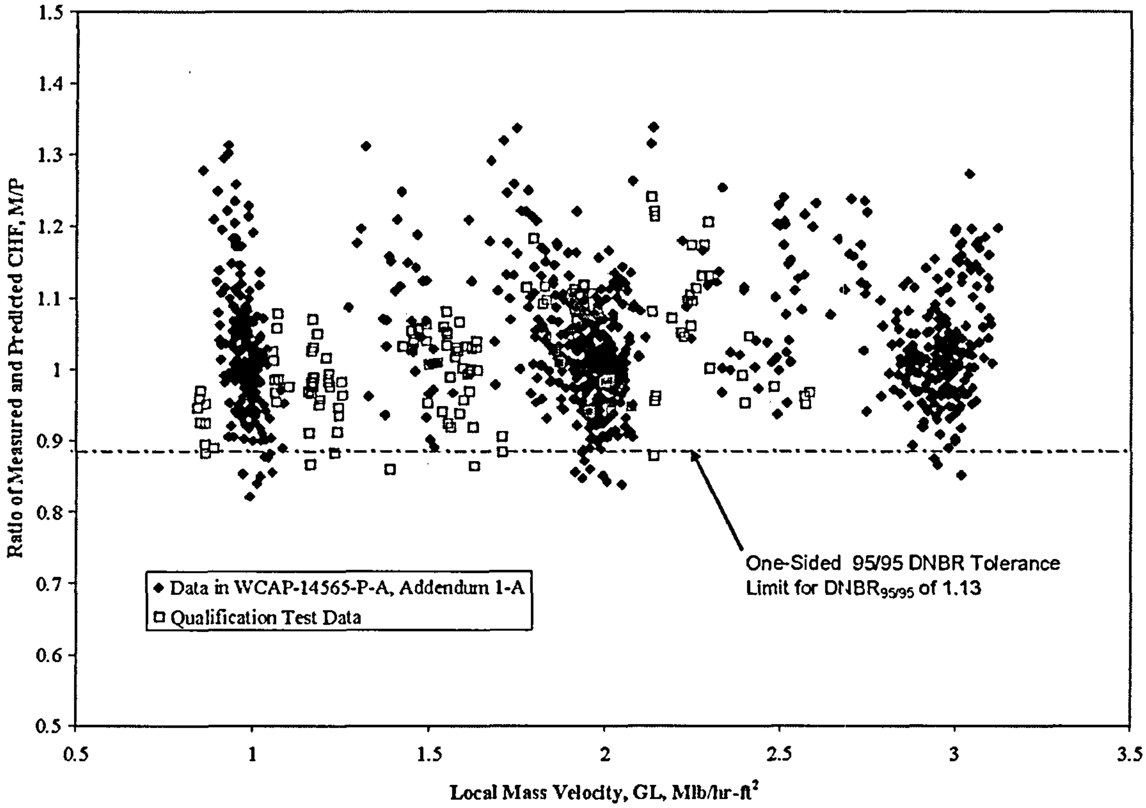

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Figure 5.2-4
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Local Quality

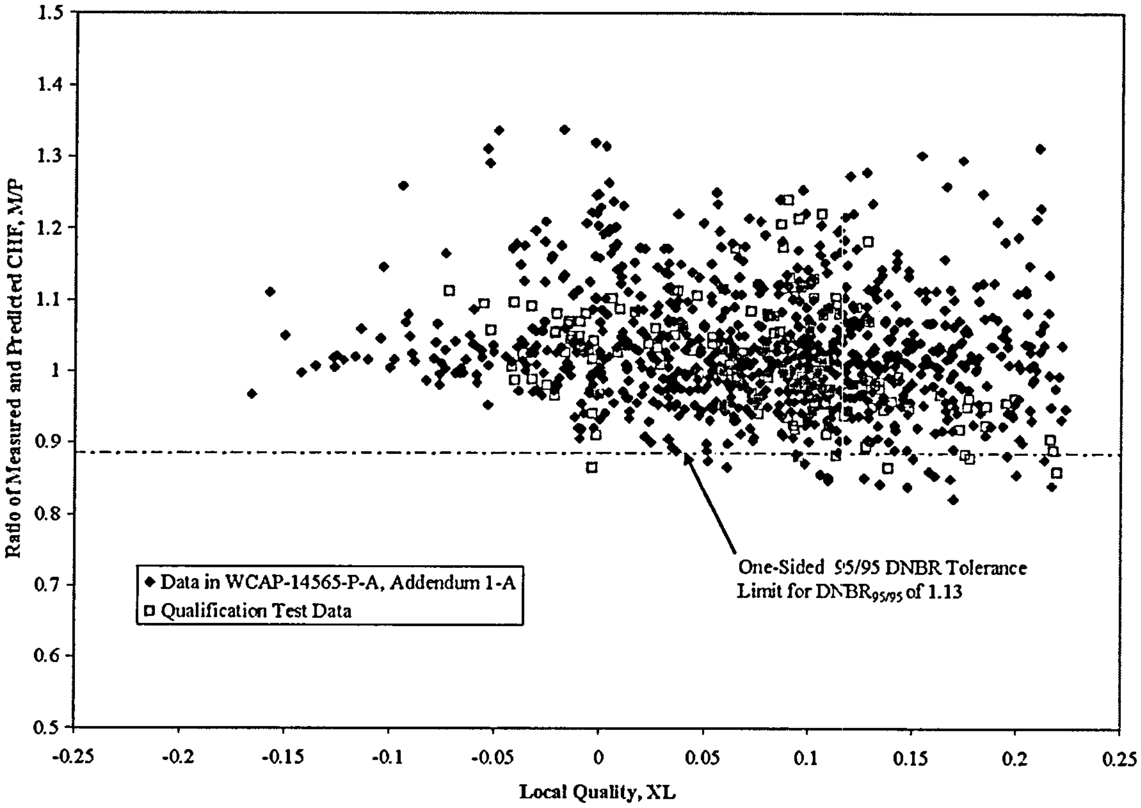

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Figure 5.2-5
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Heated Hydraulic Diameter Ratio

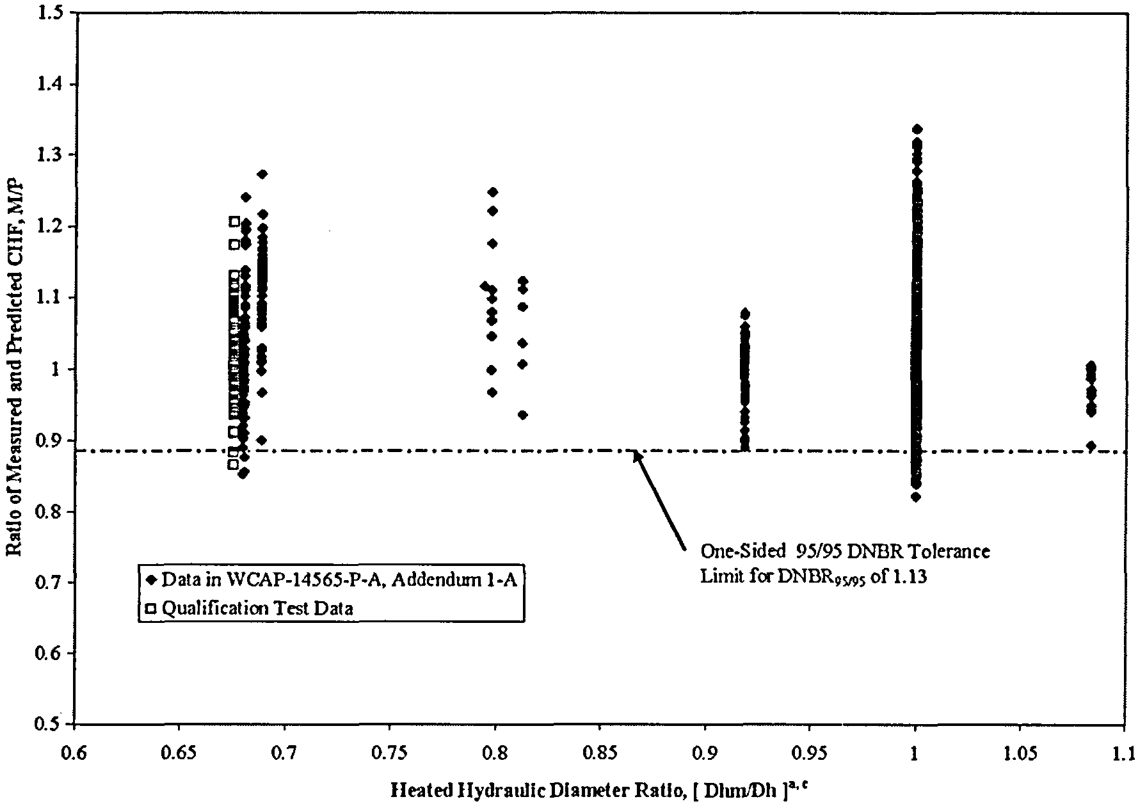

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Figure 5.2-6
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Matrix Heated Hydraulic Diameter, Dhm

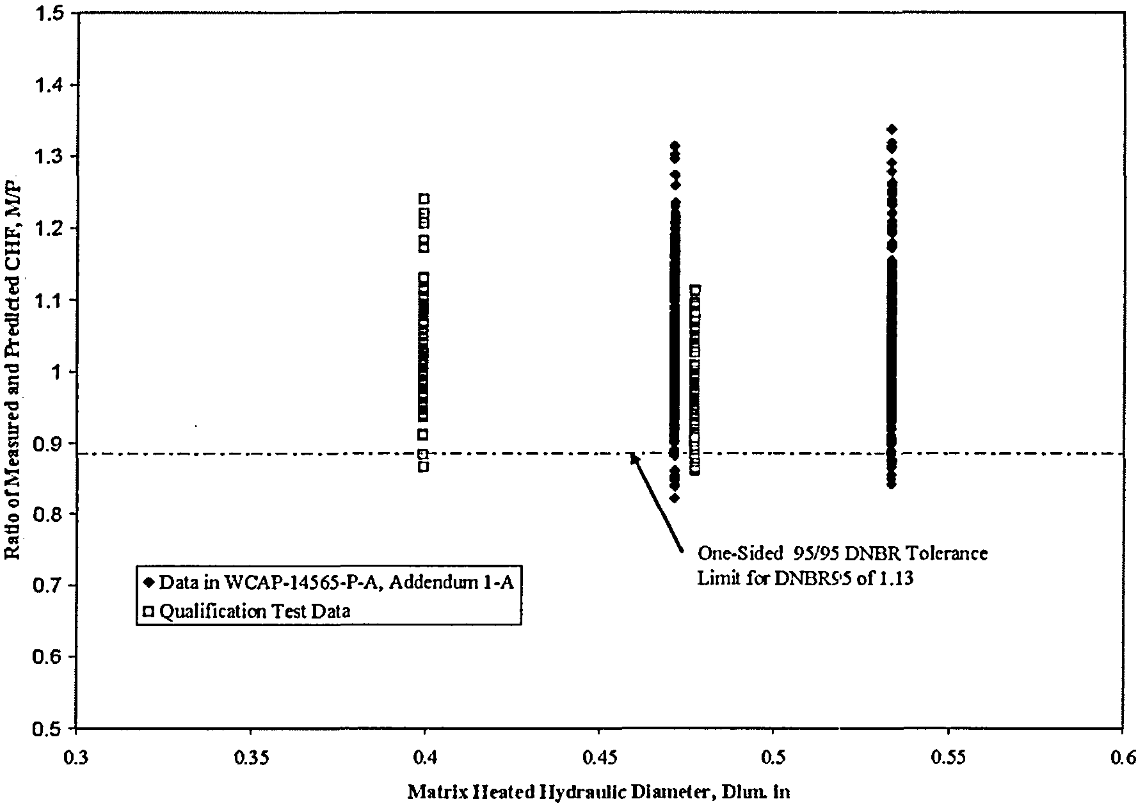

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Figure 5.2-7
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Heated Length, HL

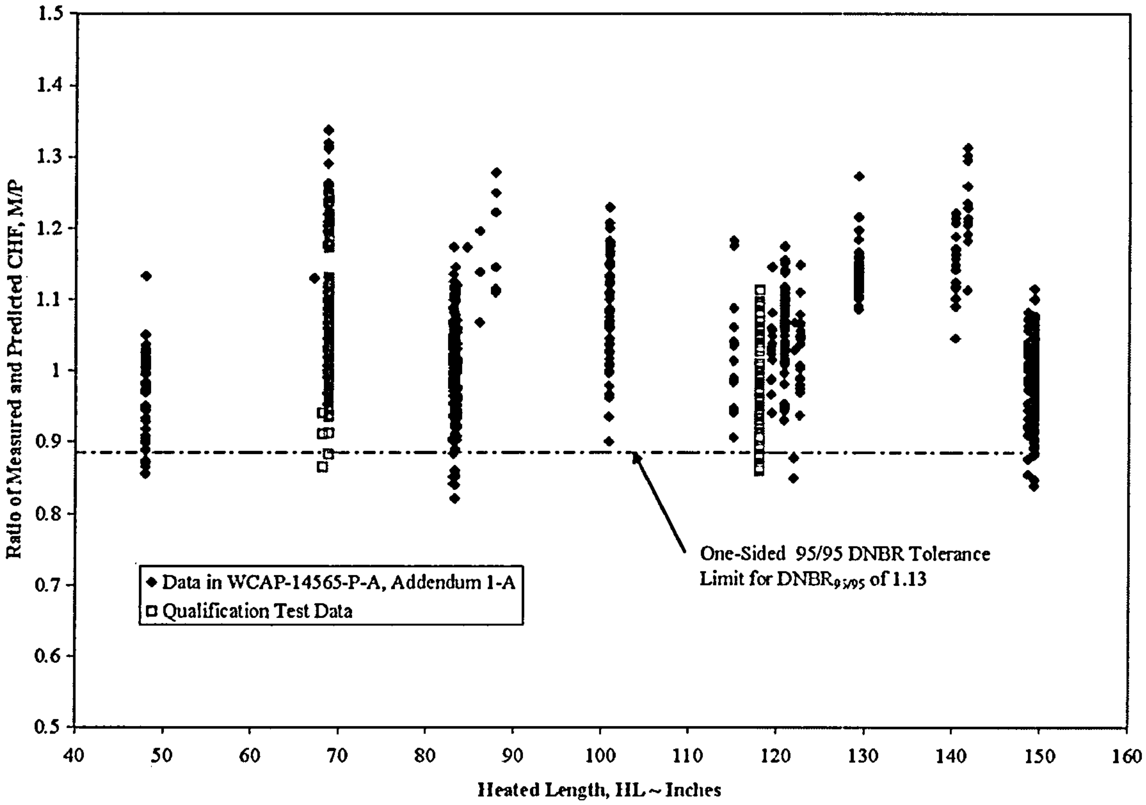

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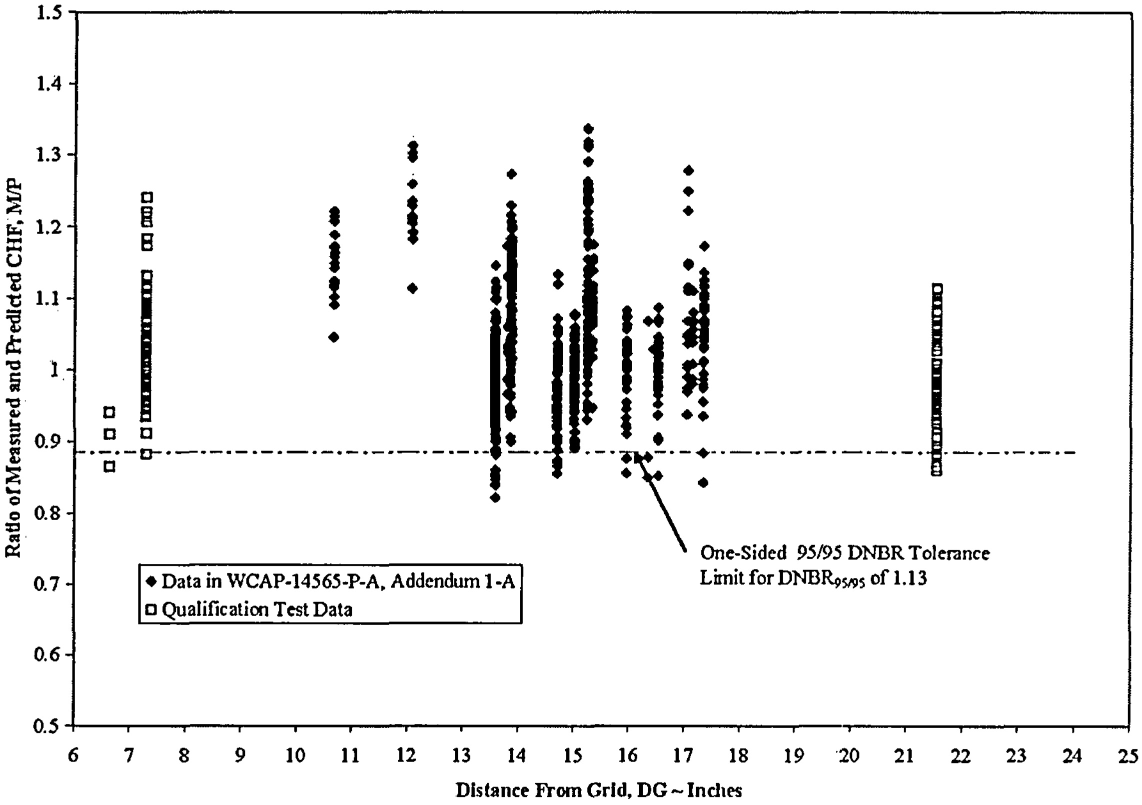
Figure 5.2-8
Plot of VIPRE/ABB-NV M/P CHF Ratio versus Distance from Grid, DG



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5.3 WLOP Correlation Statistical Evaluation and 95/95 DNBR Limit

Following the methods applied to the ABB-NV correlation in Reference 4, W and D' normality tests and comparison tests were performed to determine if the WLOP correlation and validation data were random samples from one or more populations and whether the data from individual tests and the combination of tests were normally distributed. As stated in Section 5.0, parametric comparison tests were performed to determine if data from the different test sections were poolable, then normality tests were performed on the pooled data. If the pooled data failed the normality test, non-parametric tests were performed to check the hypothesis that the averages for the pooled tests are the same. The data were examined in the following order:

1.) [

] ^{a,c}. The mean and standard deviation for the ratio of measured to WLOP predicted CHF are shown in Table 4-3 for the correlation database and the validation database. The correlation database has 441 points and the validation database has 167 points or 27.5% of the total points within the range of applicability. The Bartlett test and t-Test was applied to the data in the correlation database and validation database to verify that these data came from the same population(s). The results from the tests are summarized in Table 5.3-1. Since the [ ] ^{a,c} the D'normality test, Table 5.3-4, the results of the non-parametric analysis are also given in Table 5.3-1.

2.) The second comparison made on the data was performed to examine if there is a bias in the correlation for [ ] ^{a,c}. The comparison is made with the data from the correlation database [ ] ^{a,c}. These results of the comparison tests are summarized in Table 5.3-1. Since the [ ] ^{a,c} the D'normality test, Table 5.3-4, the results of the non-parametric analysis are also given in Table 5.3-1.

3.) Since no bias is observed between the correlation database and verification database or due to bundle array geometry, a multiple data analysis was performed on all of the test section data. The results of the parametric comparison tests are given in Table 5.3-2. Based upon these results, it is concluded that not all test sections have the same variance or mean. This is not a surprising result for a large, 18 test sections, and diverse database with tests that have a small standard deviation. Following Reference 4, [

] ^{a,c}, are identified below:

a, b, c

[ ]

It is noted that the mean M/P CHF ratio [

] $^{a, c}$ are given in Table 5.3-3. Although the tests [

] $^{a, c}$, so the data are combined.

4.) The W and D' normality tests were then applied to the data from each test section and each set of data, as shown in Table 5.3-4. In general, even for the groups that failed the normality tests, the distribution was close to normal, since many passed the Kolmogorov-Smirnov test. This is [

] $^{a, c}$. Examination of the probability plot of the data compared to the line representing the area of the Gaussian distribution indicates variation at the minimum and maximum values of the M/P CHF ratio. Based on examination of these plots, the DNBR 95/95 limit is computed based on a normal distribution and a distribution free limit and the most conservative limit is selected.

5.) The one-sided 95/95 DNBR tolerance limit for [ ] $^{a, c}$ is provided in Table 5.3-5. Based upon the data presented in this table, [

] $^{a, c}$, the DNBR limit [

] $^{a, c}$ is 1.17 and based upon the parametric technique, the limit is 1.18 using the Owen's one-sided tolerance factor$^{(18)}$. Based upon the [ ] $^{a, c}$, the DNBR limit [ ] $^{a, c}$ is 1.181 and based upon the parametric technique, the limit is 1.168 using the Owen's one-sided tolerance factor. Based upon these evaluations, the DNBR limit of 1.18 is applicable for the entire database. A plot of the measured CHF versus the WLOP predicted CHF for all the test data is given in Figure 5.3-1, along with the DNBR limit curve. The DNBR limit of 1.18 is equivalent to a value of 0.8475 for the M/P CHF ratio. It is noted that for the entire database, twenty test points, or 3.3% of the data fall below the $M/P_{95/95}$ limit of 0.8475. In [

] $^{a, c}$ fall below the limit.

The data are then examined graphically in order to check for any deviation as a function of the correlation variables. The plots of the M/P CHF ratio as a function of pressure, local mass velocity, local quality, heated hydraulic diameter ratio, matrix heated hydraulic diameter, the heated length from BOHL to location of CHF, HL and the grid spacing term, GST are shown in Figures 5.3-2 through 5.3-8. The DNBR limit is also shown on these plots to show the number of test points that fall below the limit and the location of those points.

Based upon the results of the statistical tests applied to the WLOP database and the scatter plot analysis, the one-sided 95/95 DNBR limit is determined to be 1.18. The parameter ranges for the WLOP database, including the MV grid database, are given in Table 5.3-6.

Table 5.3-1

Comparison Tests
WLOP Correlation and Validation Database
Fuel Bundle Array for Correlation Data

Bartlett Test Results - WLOP Data

Database	N	Mean	s	K	M	C	M/C	χ^2_{95}	Pass Test

a, b, c

a, b, c

t-Test Results -unequal variances - WLOP Data

Database	N	Mean	s	m1 – m2	t	$t_{975,713}$	Pass Test

a, b, c

a, b, c

Wilcoxon-Mann-Whitney Rank Sum Test Results - WLOP

Database	N	Median	m	n	T	z	zcrit	Pass Test

a, b, c

a, b, c

Table 5.3-2
Parametric Comparison Tests
Combined Correlation and Validation WLOP VIPRE Database

a, b, c

Test No.	Bundle Array	Rod Diam. ~ in.	Rod Pitch ~ in.	Heated Length ~ in.	Grid Spacing ~ in.	Guide Thimble	Axial Shape	N	WLOP M/P μ	s
	All							608	1.0009	0.0889

Bartlett Test Results - WLOP Data

Database	N	Mean	s	K	M	C	M/C	$\chi^2_{.95}$	Pass Test
ALL	608	1.0009	0.0889	18	74.04	1.0145	72.98	27.585	No

F-Test Results - WLOP Data

Database	K	N	S_1	S_2	S_1 / S_2	$F_{.95}(n_1, n_2)$	Pass Test
ALL	18	608	0.0200	0.00756	2.6451	1.64	No

Table 5.3-3
Comparison Tests for Pooled Subsets
WLOP VIPRE Database

Bartlett Test Results - WLOP Data

Database	N	Mean, μ	s	K	M	C	M/C	$\chi^2_{.95}$	Pass Test

[ ]$^{a, b, c}$

F-Test Results – WLOP Data

Database	K	N	S_1	S_2	S_1 / S_2	$F_{.95}(n_1, n_2)$	Pass Test

[ ]$^{a, b, c}$

Kruskal-Wallis Variance By Ranks Test Results – [ ]^{a,c}

Database	K	H	$\chi^2_{.95}$	Pass Test

[ ]$^{a, b, c}$

[ ]^{a,c}

[ ]^{a,c}

Table 5.3-4
W and D' Normality Tests
WLOP VIPRE Database

Data	N	Mean	D' Calculated	D' P=.025	D' P=.975	Pass Test

a, b, c

[ ]

Data	N	Mean	*W* Calculated	*W* P=.05	Pass Test

a, b, c

[ ]

[ ] ^{a,c}

[ ] ^{a,c}

Table 5.3-5
Determination of $DNBR_{95}$ Limit for Pooled Data
WLOP VIPRE Database

Calculation of $DNBR_{95}$ Limit Calculation for Parametric Data

Database	Mean	S	N	K	$DNBR_{95}$
[					]

a, b, c

Calculation of $DNBR_{95}$ Limit Calculation for Non-parametric Data

Database	γ	P	n	M	Value	$DNBR_{95}$
[						]

a, b, c

Partial Ranking of Data from [ ]a, c

a, b, c

[ ]

Table 5.3-6
Parameter Ranges for the WLOP VIPRE Correlation Database

Parameter	Minimum	Maximum
Pressure (psia)	185	1800
Local Coolant Quality	-0.04	0.75
Local Mass velocity (Mlb/hr-ft^2)	0.23	3.07
Matrix Heated Hydraulic Diameter, Dhm (inches)	0.4635	0.5334
Heated Hydraulic Diameter Ratio, [ ]^{a,c}	0.680	1.00
Heated Length, HL (inches)	48*	168
Grid Spacing Term, [ ]^{a,c}	27	95

*Note: 48 inches is set as minimum HL value in the application of the correlation, applied at all elevations below 48 inches

Figure 5.3-1
Measured and Predicted Critical Heat Fluxes
WLOP Correlation

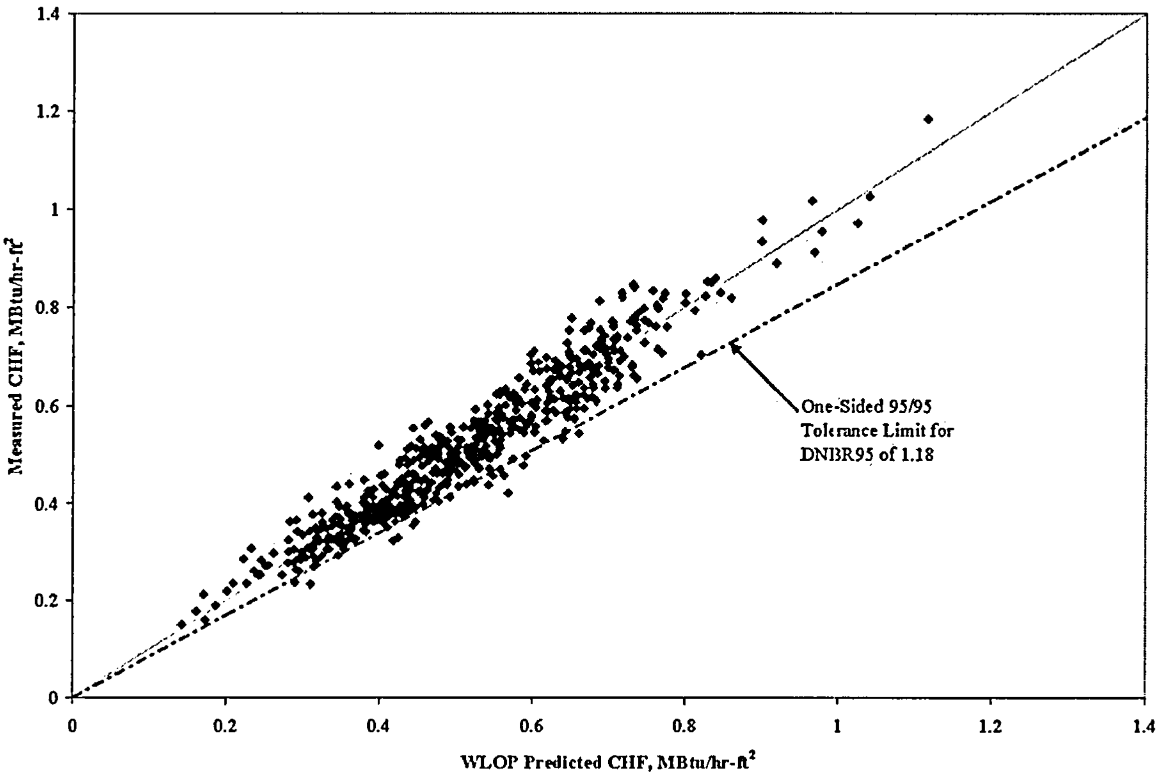

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Figure 5.3-2
Plot of M/P CHF Ratio versus Pressure
WLOP Correlation

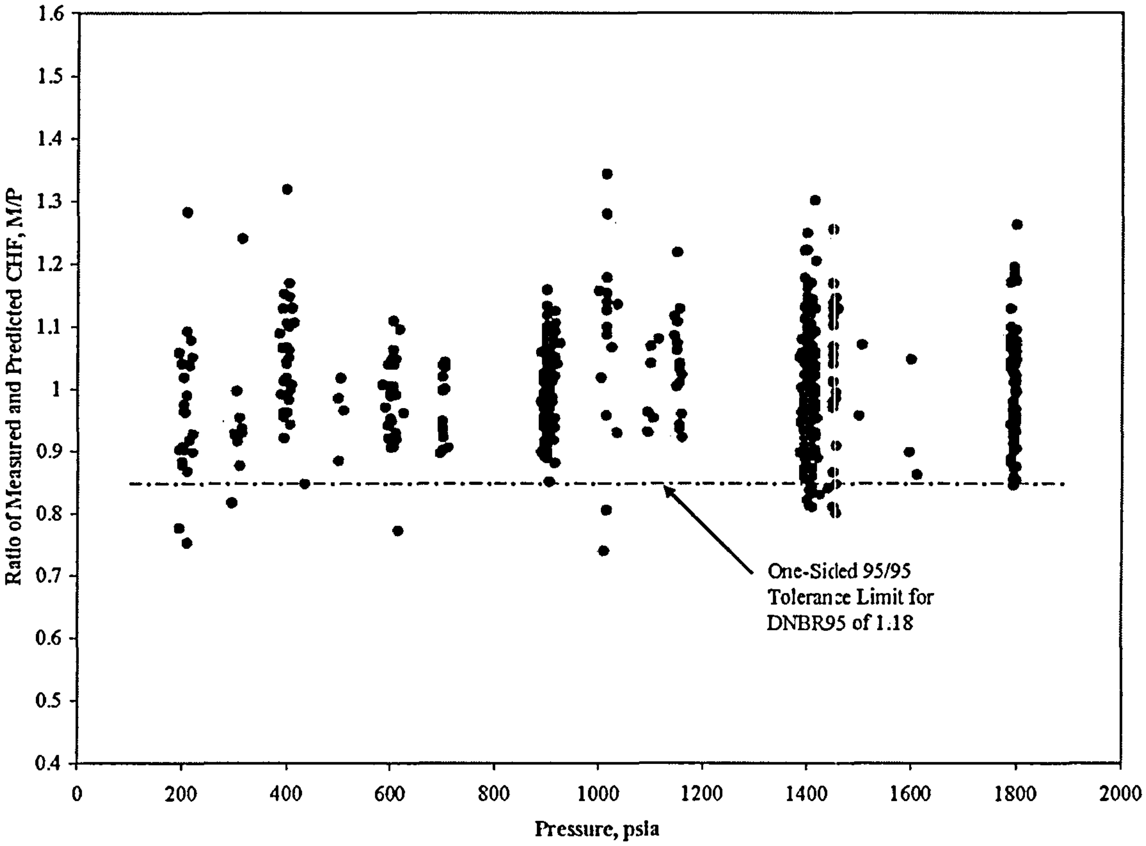

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Figure 5.3-3

Plot of M/P CHF Ratio versus Local Mass Velocity WLOP Correlation

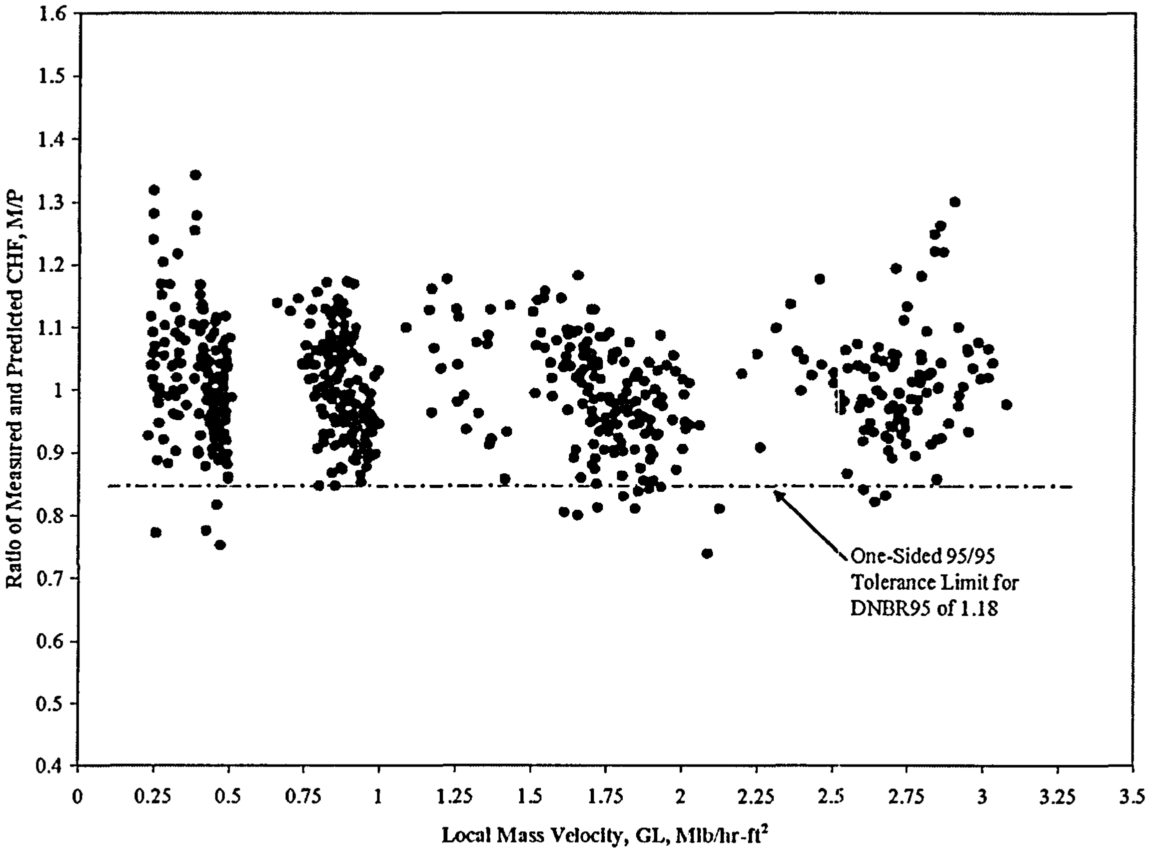

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Figure 5.3-4
Plot of M/P CHF Ratio versus Local Quality
WLOP Correlation

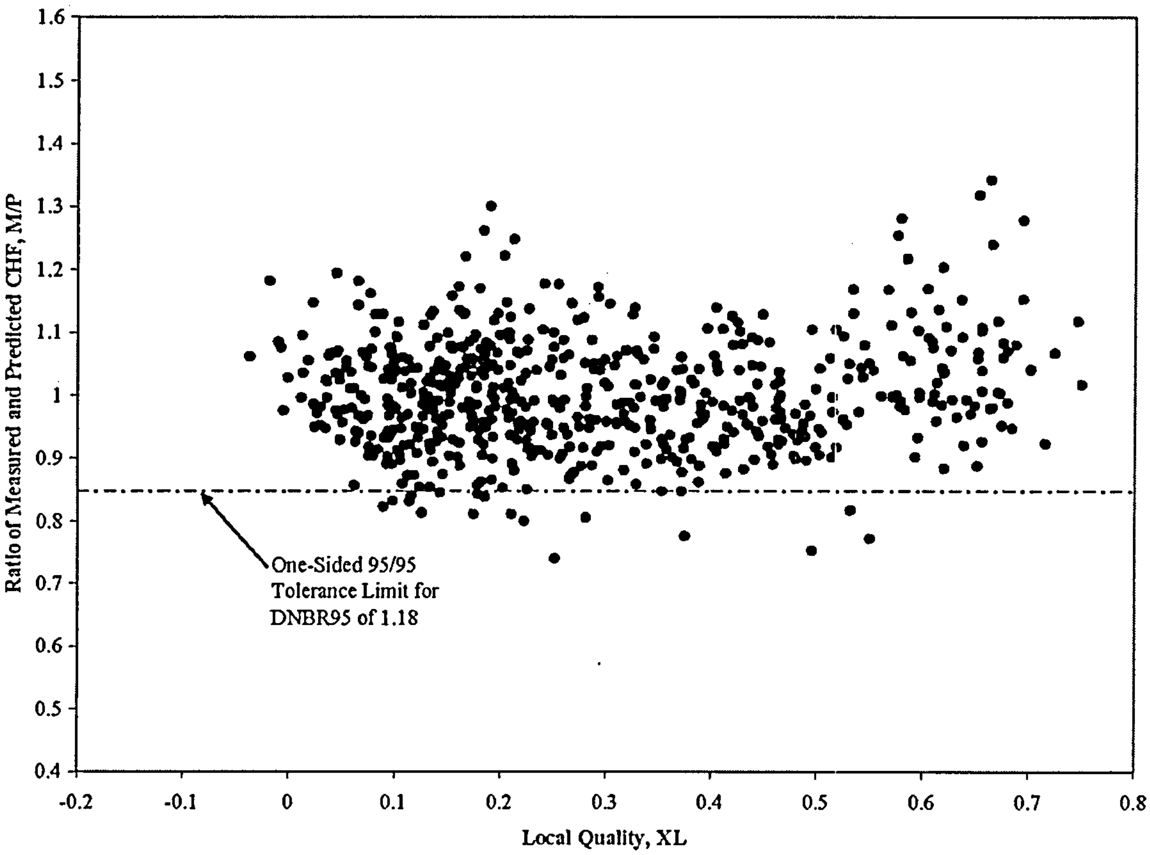

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Figure 5.3-5
Plot of M/P CHF Ratio versus Heated Hydraulic Diameter Ratio
WLOP Correlation

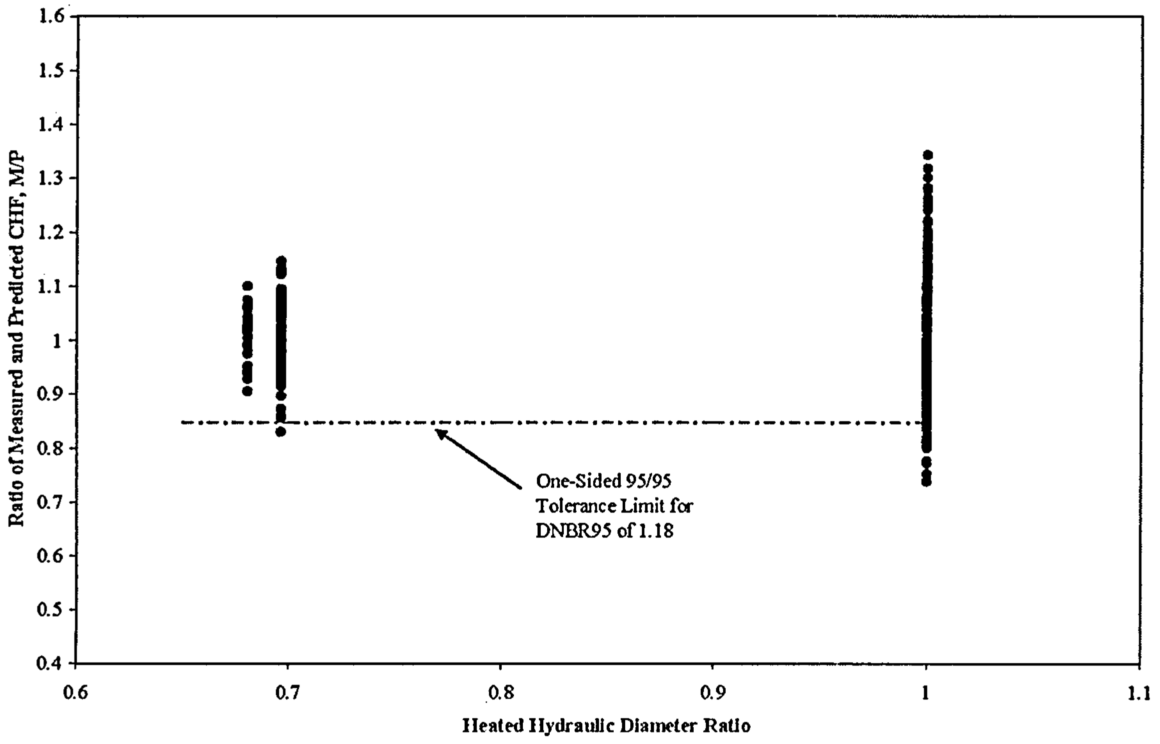

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Figure 5.3-6
Plot of M/P CHF Ratio versus Matrix Heated Hydraulic Diameter, Dhm
WLOP Correlation

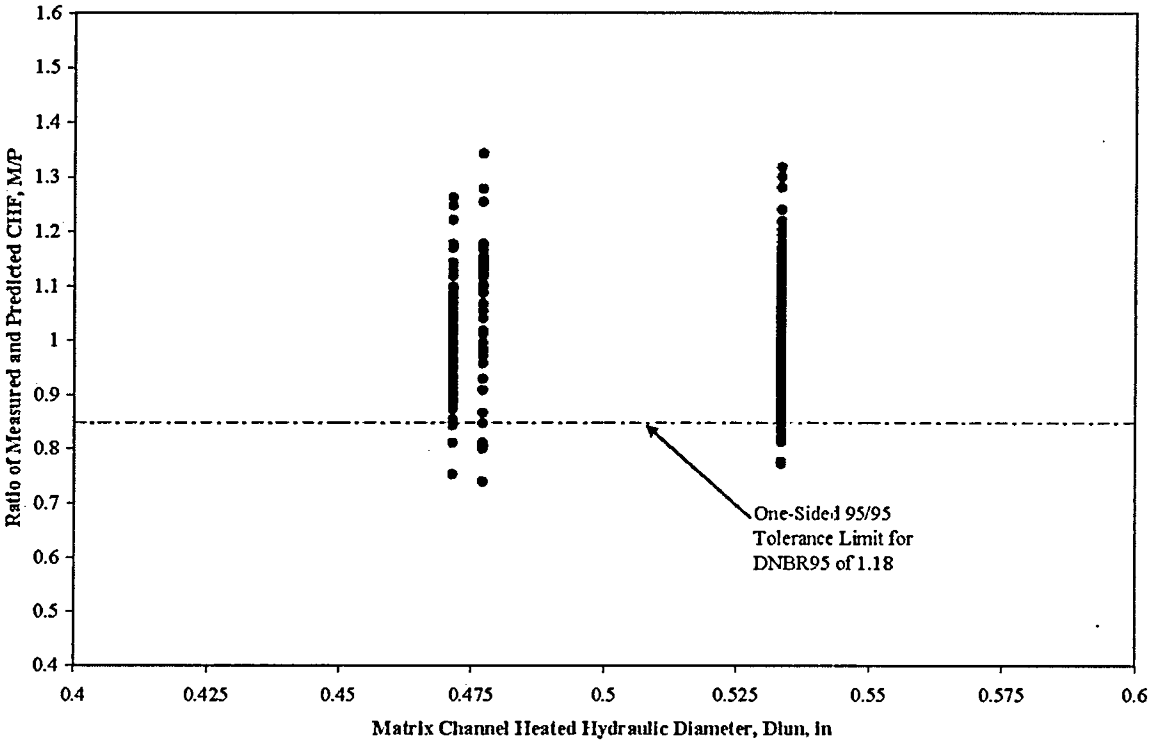

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Figure 5.3-7
Plot of M/P CHF Ratio versus Heated Length, HL
WLOP Correlation

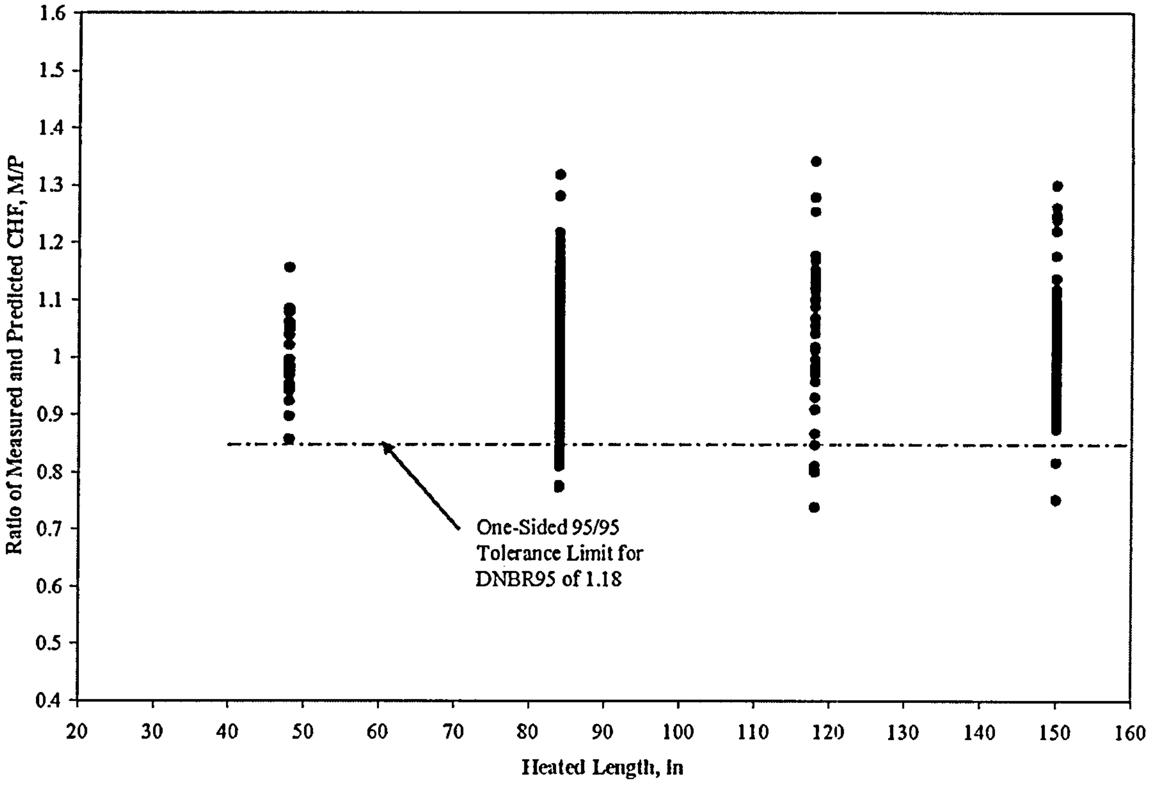

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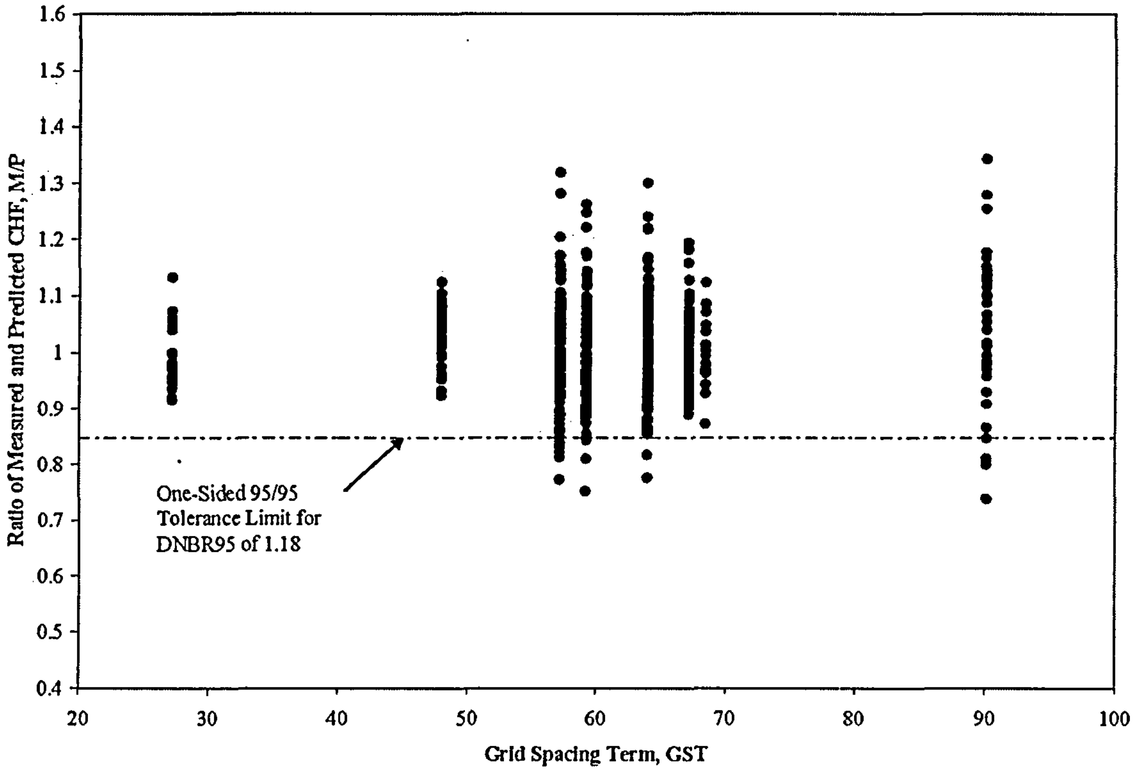
Figure 5.3-8
Plot of M/P CHF Ratio versus Grid Spacing Term, GST
WLOP Correlation



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6.0 Correlation Applications

The intended applications of ABB-NV and WLOP for Westinghouse PWR are similar to current applications of the W-3 DNB correlation(5). The intended application of WLOP for CE-PWR is similar to the current application of the MacBeth DNB correlation(6). Westinghouse intends to use the ABB-NV correlation and the WLOP correlation for evaluating margin to the CHF or DNB acceptance criterion defined in the Standard Review Plan (SRP) at the core conditions that the primary DNB correlation is not applicable. SRP Section 4.4(21) states that the DNB acceptance criterion provides assurance that there be at least a 95% probability at a 95% confidence level that the hot fuel rod in the core does not experience a DNB during normal operation or anticipated operational occurrence. The acceptance criterion is met in thermal-hydraulic design when the minimum DNBR of the hot rod in the hot channel is above the 95/95 DNBR limit of the correlation. The correlations will be used only with a computer code that has been either used for the correlation development or qualified with its 95/95 DNBR limit. Technology transfer of the ABB-NV and WLOP correlation(s) will follow through a process that meets the requirements specified in Generic Letter (GL) 83.11 Supplement 1(22), "Qualification for Performing Safety Analyses."

ABB-NV and WLOP applications will be similar to the W-3 correlation(19) used as a supplement to the primary DNB correlation for PWR fuel designs. Each correlation application is further discussed below.

6.1 ABB-NV Correlation Application to Westinghouse PWR

The ABB-NV DNB correlation with the current 95/95 DNBR limit of 1.13 and the VIPRE code will be applied to the heated length of the Westinghouse PWR fuel designs below the first mixing vane grid. The W-3 DNB correlation(19) is currently used for predicting DNBR margin in that region associated with severely bottom skewed axial power shapes simulated under the control rod withdrawal from subcritical accident for some Westinghouse PWR plants. W-3 is also used for confirming DNBR margin in that region with severely bottom skewed axial shapes from simulated accident conditions that are protected by the Thermal Over-Temperature ΔT (OTΔT) reactor trip (23) setpoints of Westinghouse NSSS PWRs, in conjunction with a revised axial offset (AO) control strategy that allows more flexible plant operation. Similar to the current W-3 application, ABB-NV will be applied to all Westinghouse PWR fuel designs, including the 14x14 fuel products with rod outside diameters (ODs) of 0.400 or 0.422 inches, the 15x15 fuel products with rod OD of 0.422 inches, the 16x16 fuel products with rod ODs of 0.360 or 0.374 inches, and the 17x17 fuel products with rod ODs of 0.360 or 0.374 inches.

The heated hydraulic diameter ratio values of the Westinghouse PWR fuel designs are within the range of the extended ABB-NV correlation database in Table 5.2-6. The heated length below the first mixing vane grid is typically less than 30 inches from the core inlet. The minimum HL of 48 inches supported by the ABB-NV database in Table 5.2-6 will be conservatively used whenever the heated length is less than 48 inches, without taking credit of any benefit from the reduced HL in the DNBR predictions.

To ensure a continuity of power shape correction in DNBR predictions between the NV and the MV grid regions, the same Fc factor used with the primary DNB correlation of the Westinghouse PWR MV grid fuel design (e.g., the Tong factor for the WRB-1 correlation in Reference 9) will be used with ABB-NV correlation. [

] ^{a,c}.

The current ABB-NV 95/95 DNBR limit of 1.13 has been confirmed with the qualification test data in this report with grid spacing ranging from 7.3 inches to 22 inches in Table 5.2-6 that is beyond the original correlation range for the distance from grid term (8 to 18.86 inches). This indicates that the correlation form for DG is sufficiently robust that the correlation can be applied for the Westinghouse PWR geometry, below the mixing vane grids. For some Westinghouse PWR fuel designs, the DG term can reach 24 inches in the NV grid region. This is a slightly larger value than the ABB-NV database, but the ABB-NV grid spacer term is nearly constant over the range from 18.86 inches to 24 inches, which is consistent with experimental observations of NV grid DNB behavior with large grid spacing. Effect of NV grid spacing change from 22 to 24 inches on DNB is less than the change from 18.86 to 22 inches. Since the effect of NV grid spacing beyond 18.86 inches is relatively small, the ABB-NV correlation can be applied at the slightly larger NV grid spacing up to 24 inches. The minimum grid spacing will be maintained at 7.3 inches for this application.

ABB-NV will be applied for calculating DNBR from the beginning of the heated length to the axial location of the first MV grid of the Westinghouse PWR fuels. The fuel region near the core or bundle inlet is typically highly subcooled with local quality value lower than - 0.14 obtained from higher elevations in the original ABB-NV database(4). In the DNB data analysis, DNBR is calculated for the entire heated length, including the highly subcooled region near the inlet. The ABB-NV DNBR predictions are very conservative at low quality conditions less than - 0.14. The conservatism in the ABB-NV predictions is demonstrated in the analysis of the DNB data from the rod bundle with a bottom peaked axial power shape (CE-Test 60) in Reference 4. The ABB-NV M/P mean for CE-Test 60 is approximately [ ] ^{a,b,c}. Therefore, while maintaining the upper quality limit of the DNB correlation, a lower quality limit is not needed for the correlation application consistent with the correlation use in data analysis. Additional conservatism is added to the ABB-NV application to Westinghouse PWR fuel designs by maintaining the minimum heated length of the correlation to 48 inches in Table 5.2-6, regardless the actual length below the first MV grid.

The extended ABB-NV applicable range for design application is summarized in Table 6.1-1. The correlation will be used with the Westinghouse version of the VIPRE code and is in full compliance with the conditions of the Safety Evaluation Report (SER) on the VIPRE code and modeling(2). Specifically,

1. The 95/95 ABB-NV DNBR limit remains to be 1.13 for Westinghouse PWR fuel design applications in the parameter range defined in Table 6.1-1.

2. Selection of the appropriate DNB correlation, DNBR limit, engineering hot channel factors for enthalpy rise and other fuel-dependent parameters for a specific plant will still be justified for each application.

3. ABB-NV will be used as a supplement to the primary DNB correlation for predicting DNBR margin in the fuel region of Westinghouse fuel designs near core inlet.

Table 6.1-1
Applicable Range of ABB-NV Correlation Extension

ABB-NV Parameter	Applicable Range
Pressure (psia)	1750 to 2415
Local mass velocity (Mlbm/hr-ft^2)	0.8 to 3.16
Local quality	≤ 0.22
Heated length, inlet to CHF location (in)	48* to 150
Heated hydraulic diameter ratio, [ ]^{a,c}	0.68 to 1.08
Grid Distance, (in)	7.3 to 24

* Although the heated length below the first mixing grid is below 48 inches, the minimum heated length used in the correlation is conservatively maintained at 48 inches.

6.2 WLOP Correlation Application

The WLOP correlation 95/95 DNBR limit with the Westinghouse version of the VIPRE-01 code (VIPRE) is 1.18. The W-3 DNB correlation(5) or the MacBeth correlation(6) is currently used for predicting DNBR margin at low pressure conditions encountered in a PWR post-trip steamline break (SLB) accident. Similar to the current W-3 application, WLOP will be applied to all Westinghouse PWR fuel designs, including the 14x14 fuel products with rod outside diameters (ODs) of 0.400 or 0.422 inches, the 15x15 fuel products with rod OD of 0.422 inches, the 16x16 fuel products with rod ODs of 0.360 or 0.374 inches, and the 17x17 fuel products with rod ODs of 0.360 or 0.374 inches. Similar to the current MacBeth application, WLOP can be applied with the VIPRE code to all current CE PWR fuel designs.

The heated hydraulic diameter ratio and heated length values for the Westinghouse PWR and CE PWR fuel designs are within the range of the WLOP database in Table 5.3-6. The minimum HL of 48 inches will be conservatively used whenever the heated length is less than 48 inches, without taking credit of any benefit from the reduced HL in the DNBR predictions.

To ensure a continuity of power shape correction in DNBR predictions between the pressure regions, the same Fc factor used with the primary DNB correlation of the PWR fuel design will be used with the WLOP DNB correlation. The original Tong factor(19) will be used for Westinghouse PWR fuel designs, as it has been used with WRB-1(9), WRB-2(10) and WRB-2M(24) (e.g., the Tong factor for the WRB-1 correlation in Reference 9) will be used with WLOP correlation. The optimized Fc factor from the ABB-NV correlation(4) will continue to be used for CE PWR fuel designs, as it has been used with

ABB-NV, ABB-TV(4) and WSSV(11). [

]^{a,c}.

The data range of the WLOP grid spacing term [ ]^{a,c} is between 27 and 95. For some Westinghouse PWR fuel designs, the maximum grid spacing term can reach 114. This is a slightly larger value than the WLOP database, but the WLOP grid spacer term is essentially 1.0 above the value of 70, consistent with experimental observations of NMV grid performance with large grid spacing. Since WLOP predictions show no trend with respect to grid spacing and are not affected by a change in the grid spacing term from 95 to 115, the correlation can be applied to the maximum [ ]^{a,c} less than 115. The minimum grid spacing will be maintained to greater than 27.

Similar to the ABB-NV correlation, WLOP provides conservative DNBR predictions at low local quality conditions. While maintaining the upper quality limit of the DNB correlation, a lower quality limit is not needed for the correlation application consistent with the correlation use in data analysis. Additional conservatism is added to the WLOP application by maintaining the minimum heated length of the correlation to 48 inches in Table 5.3-6, regardless the actual length below the first MV grid.

The WLOP applicable range is summarized in Table 6.2-1. The correlation will be used with the Westinghouse version of the VIPRE code and is in full compliance with the conditions of the Safety Evaluation Report (SER) on the VIPRE code and modeling(2). Specifically,

1. The 95/95 WLOP DNBR limit is 1.18 in the parameter range defined in Table 6.2-1.
2. Selection of the appropriate DNB correlation, DNBR limit, engineering hot channel factors for enthalpy rise and other fuel-dependent parameters for a specific plant will still be justified for each application.
3. WLOP will be used as a supplement to the primary DNB correlation for predicting DNBR margin under low pressure conditions.

Table 6.2-1
Applicable Range of WLOP CHF Correlation

Parameter	Applicable Range
Pressure (psia)	200 to 1800
Local Coolant Quality	$\leq$ 0.75
Local Mass velocity (Mlb/hr-ft^2)	0.23 to 3.07
Matrix Heated Hydraulic Diameter, Dhm (inches)	0.4635 to 0.5334
Heated Hydraulic Diameter Ratio, [ ]^{a,c}	0.679 to 1.00
Heated Length, HL (inches)	48* to 168
Grid Spacing Term	27 to 115

* Set as minimum HL value, applied at all elevations below 48 inches

7.0 Conclusions

The following conclusions and restrictions apply for the application of ABB-NV to the heated length below the first MV grid and the application of the WLOP correlation:

1. Analysis of supplemental non-mixing grid data with rod diameters of 0.36 and 0.374 inches demonstrate the applicability of the ABB-NV correlation to the Westinghouse PWR fuel designs in the heated length below the first mixing grid.

2. Analysis of the supplemental data indicate the data are poolable with the original data and the approved DNBR limit of 1.13 for the ABB-NV correlation for CE-PWR applications is maintained for the Westinghouse PWR applications within the parameter range in Table 6.1-1.

3. Analysis of the modified ABB-NV correlation (WLOP) for low pressure and low flow conditions and the source and validation data indicates that a minimum DNBR limit of 1.18 for the WLOP correlation will provide a 95% probability with 95% confidence of not experiencing CHF on a rod showing the limiting value.

4. The WLOP correlation with the 95/95 DNBR limit of 1.18 can be applied to the low pressure conditions within the parameter range in Table 6.2-1, similar to the W-3 application for Westinghouse PWR and to the MacBeth application for CE PWR plants.

5. The ABB-NV correlation for Westinghouse PWR applications and the WLOP correlation must be used in conjunction with the Westinghouse version of the VIPRE-01 (VIPRE) code since the correlations were justified and developed based on VIPRE and the associated VIPRE modeling specifications.

6. The ABB-NV correlation and the WLOP correlation must use the same F_C factor for power shape correction as used in the primary DNB correlation for a specific fuel design.

7. Selection of the appropriate DNB correlation, DNBR limit, engineering hot channel factors for enthalpy rise and other fuel-dependent parameters for a specific plant will be justified for each application.

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Appendix A
ABB-NV Correlation Extension Qualification Database

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Appendix A
ABB-NV Correlation Extension Qualification Database

A detailed summary of the supplemental qualification database for application of ABB-NV for the non-mixing vane region in Westinghouse PWR is shown in Table A-1. The table in this appendix summarizes the raw data from the CHF tests, the test geometry information needed for the correlation application, the local coolant conditions at the MDNBR location taken from the VIPRE runs. It is noted that the original VIPRE database used in the analysis is documented in Reference 3. The tabulation presented here gives the data from all CHF experiments identified as Tests 190 and 175 described in Table 2-1. Nomenclature for heading abbreviations in Appendix A are defined below:

TS = Test Section Number
TD = Test Section Type (UM is Uniform Shape without Guide Thimble, UT is Uniform Shape with Guide Tube)
Press = Test Section Pressure (psia)
Tin = Test Section Inlet Temperature (°F)
Gavg = Average Test Section Mass Velocity (Mlbm/hr-ft^2)
Qavg = Test Section Critical Bundle Average Heat Flux (MBtu/hr-ft^2)
DROD = Primary DNB Rod Thermocouple Number
DCH = VIPREW Subchannel Number Where Local Coolant Conditions are Selected
GL = Local Mass Velocity in CHF Channel (Mlbm/hr-ft^2)
XL = Local Quality in CHF Channel
CHFm = Measured CHF (MBtu/hr-ft^2)
F_C = Non-uniform Shape Factor = 1.00 for Uniform Axial Power Shape
GS = Nominal [ ]^{a,c} Grid Spacing from [ ]^{a,c} (in)
HL = Heated Length to CHF Site (in)
DG = Distance from [ ]^{a,c} of Grid to CHF Site (in)
De = Wetted Hydraulic Diameter of CHF Channel (in)
Dh = Heated Hydraulic Diameter of CHF Channel (in)
Dhm = Heated Hydraulic Diameter of Matrix Channel (in)

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Table A-1
ABB-NV Correlation Extension Qualification Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

a, b, c

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table A-1 (Cont.)
ABB-NV Correlation Extension Qualification Database

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

a, b, c

Table A-1 (Cont.)

ABB-NV Correlation Extension Qualification Database

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	Dc	Dh	Dhm

a, b, c

Appendix B

ABB-NV Correlation Extension Qualification Test VIPRE Statistical Output

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Appendix B
ABB-NV Correlation Extension Qualification Test VIPRE Statistical Output

A detailed summary of the statistical output of the ABB-NV correlation Qualification Tests is given in Table B-1. The detailed statistical output for the original test data are given in Reference 3. For each test run in Table B-1, the values for the correlation variables, the measured CHF and ABB-NV predicted CHF with the VIPRE code are given, along with the value for the M/P CHF ratio. The individual test section, database, Subset, and overall statistics are given at the end of the output in Table B-1 for all tests including the original test data documented in Reference 3. Nomenclature for heading abbreviations in Appendix B are defined below:

TS = Test Section Number
TD = Test Section Type (UM is Uniform Shape without Guide Thimble, UT is Uniform Shape with Guide Thimble)
Press = Test Section Pressure (psia)
GL = Local Mass Velocity in CHF Channel (Mlbm/hr-ft^2)
XL = Local Quality in CHF Channel
F_C = Non-uniform Shape Factor = 1.00 for Uniform Axial Power Shape
GS = [ ]^{a,c} Nominal Grid Spacing, [ ]^{a,c} (in)
HL = Heated Length to CHF Site (in)
DG = Distance from [ ]^{a,c} of Grid to CHF Site (in)
De = Hydraulic Diameter of CHF Channel (in)
Dh = Heated Hydraulic Diameter of CHF Channel (in)
Dhm = Heated Hydraulic Diameter of Matrix Channel (in)
CHFm = Measured CHF (MBtu/hr-ft^2)
CHFp = ABB-NV Predicted CHF divided by F_C, (MBtu/hr-ft^2)

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Table B-1
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	De	Dh	Dhm	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table B-1 (Cont.)

Statistical Output of ABB-NV Extension Qualification VIPRE Database

<u>Original Database Plus Qualification Database – Excludes Tests 60 and 66</u>

a, b, c

[ ]

Table B-1 Continued
Statistical Output of ABB-NV Extension Qualification VIPRE Database

a, b, c

[

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Appendix C
WLOP VIPRE Database

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Appendix C
WLOP VIPRE Database

A detailed summary of the WLOP Correlation Database is shown in Table C-1 and the Validation Database is shown in Table C-2. The tables in this appendix summarize the raw data from Columbia data files, the test geometry information needed for the correlation development, the predicted local coolant conditions taken from the VIPRE runs. The tabulation presented here gives the data from all CHF experiments with test sections described in Table 2-2. Repeat runs in the correlation database, runs with only cold rods indicating DNB and outlier points from Section 4, identified in bold Italics, were eliminated in the correlation codes along with points outside the correlation parameter limits. Nomenclature for heading abbreviations is defined below:

TS = Test Section Number
TD = Test Section Type (UM is Uniform Shape without Guide Thimble, UT is Uniform Shape with Guide Tube)
Press = Test Section Pressure (psia)
Tin = Test Section Inlet Temperature (°F)
Gavg = Average Test Section Mass Velocity (Mlbm/hr-ft^2)
Qavg = Test Section Critical Bundle Average Heat Flux (MBtu/hr-ft^2)
DROD = Primary DNB Rod Thermocouple Number
DCH = VIPREW Subchannel Number Where Local Coolant Conditions are Selected
GL = Local Mass Velocity in CHF Channel (Mlbm/hr-ft^2)
XL = Local Quality in CHF Channel
CHFm = Measured CHF (MBtu/hr-ft^2)
F_C = Non-uniform Shape Factor = 1.00 for Uniform Axial Power Shape
GS = [ ]^{a,c} of Grid (in)
HL = Heated Length to CHF Site (in)
DG = Distance from [ ]^{a,c} to CHF Site (in)
De = Wetted Hydraulic Diameter of CHF Channel (in)
Dh = Heated Hydraulic Diameter of CHF Channel (in)
Dhm = Heated Hydraulic Diameter of Matrix Channel (in)

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Table C-1
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-1 (Cont.)
WLOP Correlation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2
WLOP Validation Database

a, b, c

TS TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont)
WLOP Validation Database

a, b, c

TS TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

Table C-2 (Cont.)
WLOP Validation Database

a, b, c

TS	TD	Run	Press.	Tin	Gavg	Qavg	DROD	DCH	GL	XL	CHFm	FC	GS	HL	DG	De	Dh	Dhm

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Appendix D
WLOP VIPRE Statistical Output

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Appendix D: WLOP VIPRE Statistical Output

A detailed summary of the statistical output of the WLOP correlation is given in Table D-1. For each test run in Table D-1, the values for the correlation variables, the measured CHF and WLOP predicted CHF with the VIPRE code are given, along with the value for the M/P CHF ratio. The repeat test runs and any test runs with variables outside the correlation parameter range are removed from Table D-1. The individual test section, database, Subset, and overall statistics are given at the end of the output in Table D-1. Nomenclatures for table heading abbreviations are given below:

TS = Test Section Number
TD = Test Section Type (UM is Uniform Shape without Guide Thimble, UT is Uniform Shape with Guide Thimble)
Press = Test Section Pressure (psia)
GL = Local Mass Velocity in CHF Channel (Mlbm/hr-ft^2)
XL = Local Quality in CHF Channel
F_C = Non-uniform Shape Factor = 1.00 for Uniform Axial Power Shape
GS = [ ]^{a,c} of Grid (in)
HL = Heated Length to CHF Site (in)
DG = Distance from [ ]^{a,c} to CHF Site (in)
De = Hydraulic Diameter of CHF Channel (in)
Dh = Heated Hydraulic Diameter of CHF Channel (in)
Dhm = Heated Hydraulic Diameter of Matrix Channel (in)
CHFm = Measured CHF (MBtu/hr-ft^2)
CHFp = WLOP Predicted CHF divided by F_C, (MBtu/hr-ft^2)

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Table D-1
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

a, b, c

Table D-1 (Cont.)
Statistical Output of WNGF-SSV Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WNGF-SSV Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WNGF-SSV Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

a, b, c

TS TD	Run	Press.	GL	XL	FC	GS	HL	DG	Dh	Dhm	GST	CHFm	CHFp	M/P-1	M/P

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

Correlation Database

a, b, c

Validation Database

a, b, c

Table D-1 (Cont.)
Statistical Output of WLOP Correlation VIPRE Database

<u>Combined Database</u>

a, b, c

[ ]

[ ]a, c

a, b, c

[ ]

[ ]a, c

a, b, c

[ ]

[ ]a, c

a, b, c

[ ]

[ ]a, c

a, b, c

[ ]

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Appendix E
WLOP CHF Test Geometries

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Appendix E: WLOP CHF Test Geometries

The test section radial and axial geometries for the tests used in the development and validation of the WLOP correlation not provided in Section 2.0 or Appendix E of Reference 4 are shown in Figures E-1 through E-20. The geometry for the tests used in the ABB-NV correlation development are shown in Appendix E of Reference 4 and the geometry for Test 190 is shown in Section 2.0.

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Figure E-1
Radial Geometry – CHF Test Section 9

a, b, c

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Figure E-2
Axial Geometry – CHF Test Section 9

a, b, c

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Figure E-3
Radial Geometry – CHF Test Section 10

a, b, c

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Figure E-4
Axial Geometry – CHF Test Section 10

a, b, c

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Figure E-5
Radial Geometry – CHF Test Section 13

a, b, c

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Figure E-6
Axial Geometry – CHF Test Section 13

a, b, c

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Figure E-7
Radial Geometry – CHF Test Section 19

a, b, c

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Figure E-8
Axial Geometry – CHF Test Section 19

a, b, c

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Figure E-9
Radial Geometry – CHF Test Section 30

a, b, c

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Figure E-10
Axial Geometry – CHF Test Section 30

a, b, c

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Figure E-11
Radial Geometry – CHF Test Section 33

a, b, c

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Figure E-12
Axial Geometry – CHF Test Section 33

a, b, c

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Figure E-13
Radial Geometry – CHF Test Section 35

a, b, c

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Figure E-14
Axial Geometry – CHF Test Section 35

a, b, c

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Figure E-15
Radial Geometry – CHF Test Section 37

a, b, c

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Figure E-16
Axial Geometry – CHF Test Section 37

a, b, c

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Figure E-17
Radial Geometry – CHF Test Section 39

a, b, c

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Figure E-18
Axial Geometry – CHF Test Section 39

a, b, c

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Figure E-19
Radial Geometry – CHF Test Section 42

a, b, c

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Figure E-20
Axial Geometry – CHF Test Section 42

a, b, c