



SOURCE REFERENCE RECORD (FOR TOPICAL REPORTS)

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Framatome ANP, Inc.

BAW-10199
The BWU Critical Heat Flux Correlations

Appendix I

The BWU-B11R CHF Correlation for the Mark-B11 Spacer Grid

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1.0 Introduction

In the original issue of this topical, Reference 1, the BWU CHF correlation form was developed and applied to 3 types of PWR spacer grids: the BWU-Z correlation for the Mark-BW17 design, the BWU-I correlation for standard mixing vane spacer grids other than the high performance Mark-BW17 design and the BWU-N correlation for all non-mixing vane designs.

Subsequent testing and development resulted in the Mark-B11 15x15 spacer grid design and the Mark-BW mid-span-mixing (MSM) grid design. The Mark-B11 design was qualified for CHF analysis with the BWU-Z CHF correlation with a simple multiplier on the calculated CHF ([]) in Addendum 1, Reference 2, (for tests 26.0, 27.1, 28.0, 29.0 and 30.0). Likewise, the Mark-BW MSM design was qualified for CHF analysis with the BWU-Z CHF correlation with a different multiplier on the calculated CHF ([]) in Addendum 2, Reference 3, (for tests 18.0, 18.1 and 43.0) to reflect the CHF improvement attributed to the mid-span mixing grids.

Since the approval of the BWU-Z correlation application for the Mark-B11 spacer grid design in Reference 2, Framatome ANP has concluded that the CHF database for the Mark-B11 15x15 spacer grid design merits a dedicated CHF correlation with its specific applicability range. This new correlation (BWU-B11R) is presented in this addendum and is based solely on the 222 data from five different Mark-B11-CHF tests. As such the BWU-B11R CHF correlation is more representative of the Mark-B11 15x15 CHF performance than the BWU-Z correlation with the [] multiplier.

2.0 Data and Method

The bundle condition CHF test data for the Mark-B11 design was reported in Table E-6 of Addendum 1. This 216 point database reflected the deletion of 3 outliers and 3 out of range conditions data in order to adjust the database to the BWU-Z CHF correlation using the [] multiplier.

For this dedicated BWU-B11R correlation the full set of 222 data were recorrelated (the BWU uniform CHF coefficients were re-optimized). The final form required the deletion of only one outlier (8.7 standard deviations below the mean M/P CHF) and included the 3 out of range conditions. Examination of the new statistics and bias plots demonstrate that, as expected, the BWU-B11R correlation is a superior representation of the Mark-B11 CHF performance as compared to the BWU-Z correlation when applied with the [] multiplier.

3.0 Overall Performance

For the 221 final data, the mean M/P CHF with the BWU-B11R correlation was 1.0023 with a standard deviation of 0.0679. The statistics are broken down by independent variable in Tables I-1 through I-4. A visual representation of the data is provided in Figures I-1 through I-5.

4.0 Design Limit and Range of Applicability

The optimized coefficients for the BWU-B11R CHF correlation are shown in Table I-5. As required for application of the Owen design limit, Reference 4, and used in Reference 1, the entire data set passes the D prime normality test, Reference 5, at the 5 percent level. The D prime value is 935.65. The corresponding upper and lower critical values from Reference 5 are 936.98 and 911.26. The design limit (DNBR(L)) is developed below (as in Reference 1) and is 1.145.

n , # of data = 221

N , degrees of freedom (221-14-1) = 206

M/P, average measured to predicted CHF = 1.0023

$\sigma_{M/P}$, standard deviation of the M/P values = .0679

σ_N , standard deviation adjusted for degrees of freedom = .0702

$K_{221,0.95,0.95} = 1.8414$ (Table 4.2 in Reference 4)

$$\text{DNBR(L)} = 1/(M/P - K_{221,0.95,0.95} \sigma_N) = 1/(1.0023 - 1.8414 \times 0.0702) = 1.145$$

The M/P CHF for the outlier (data id 29064) is 0.4143. Its exclusion is justified by the fact that it is 8.7 standard deviations below the mean. The limits of application for the BWU-B11R CHF correlation are given in the Table I-6. Finally, the results of application of the BWU-B11R CHF correlation over the entire Mark-B11 database are shown in Table I-7.

5.0 Conclusion

It has been shown here that the BWU-B11R CHF correlation is a superior representation of the Mark-B11 spacer grid CHF performance. It has a design limit of 1.145, is subject to the limitations of Table I-6 and is applicable solely to the Mark-B11 spacer grid design.

6.0 References

1. D. A. Farnsworth and G. A. Meyer, "The BWU Critical Heat Flux Correlations," BAW-10199P-A, August 1996.
2. D. A. Farnsworth and G. A. Meyer, "The BWU Critical Heat Flux Correlations: Applications to the Mark-B11 and Mark-BW17 MSM Designs," BAW-10199P-A, Addendum 1, December 2000.
3. D. A. Farnsworth and G. A. Meyer, "The BWU Critical Heat Flux Correlations: Application of the BWU-Z CHF Correlation to the Mark-BW17 Fuel Design with Mid-Span Mixing Grids," BAW-10199P-A, Addendum 2, June 2002.
4. D. B. Owens, "Factors for One-Sided Tolerance Limits," Sandia Corporation Monograph, March 1963.
5. M. G. Natrella, "Experimental Statistics," National Bureau of Standards Handbook, 1963.

Figure I-1

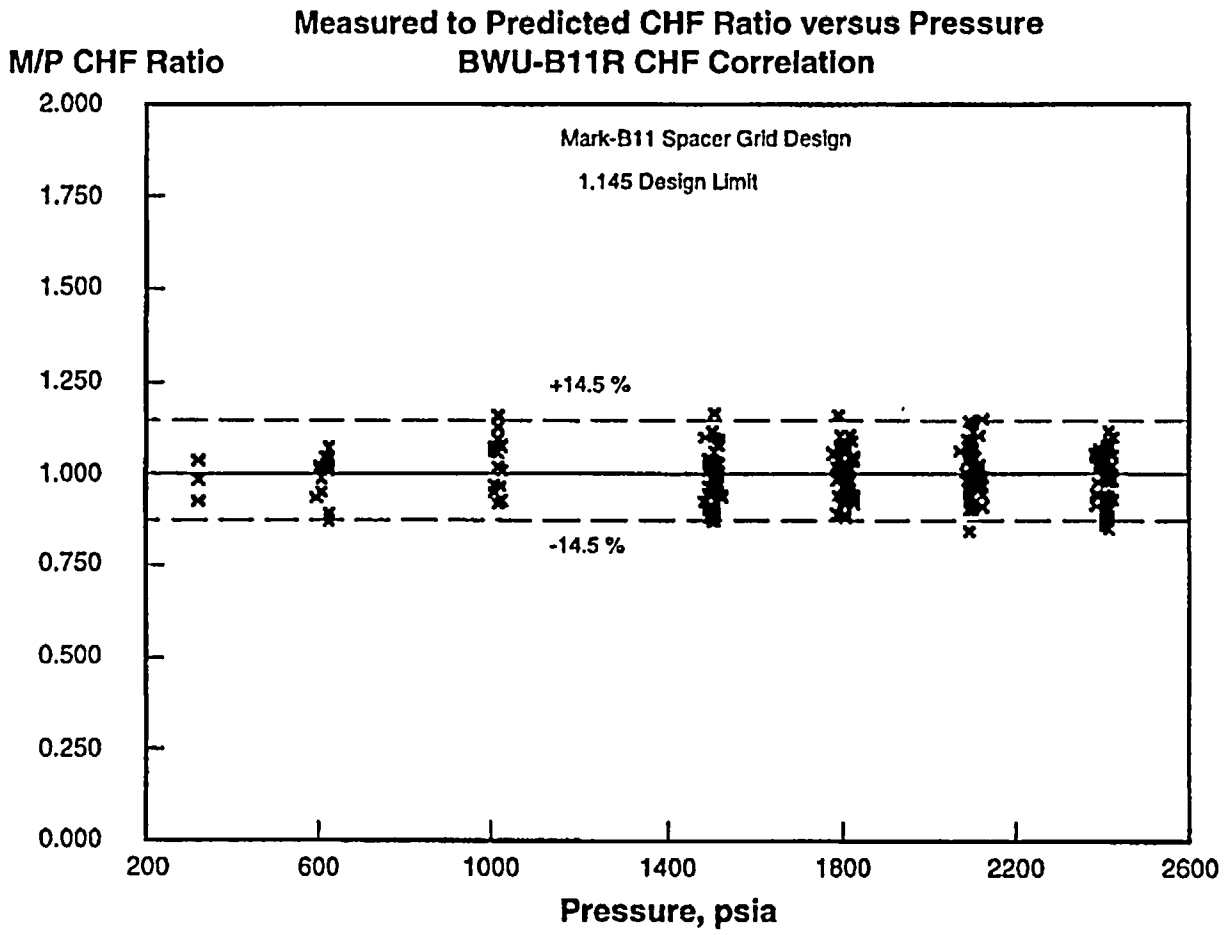
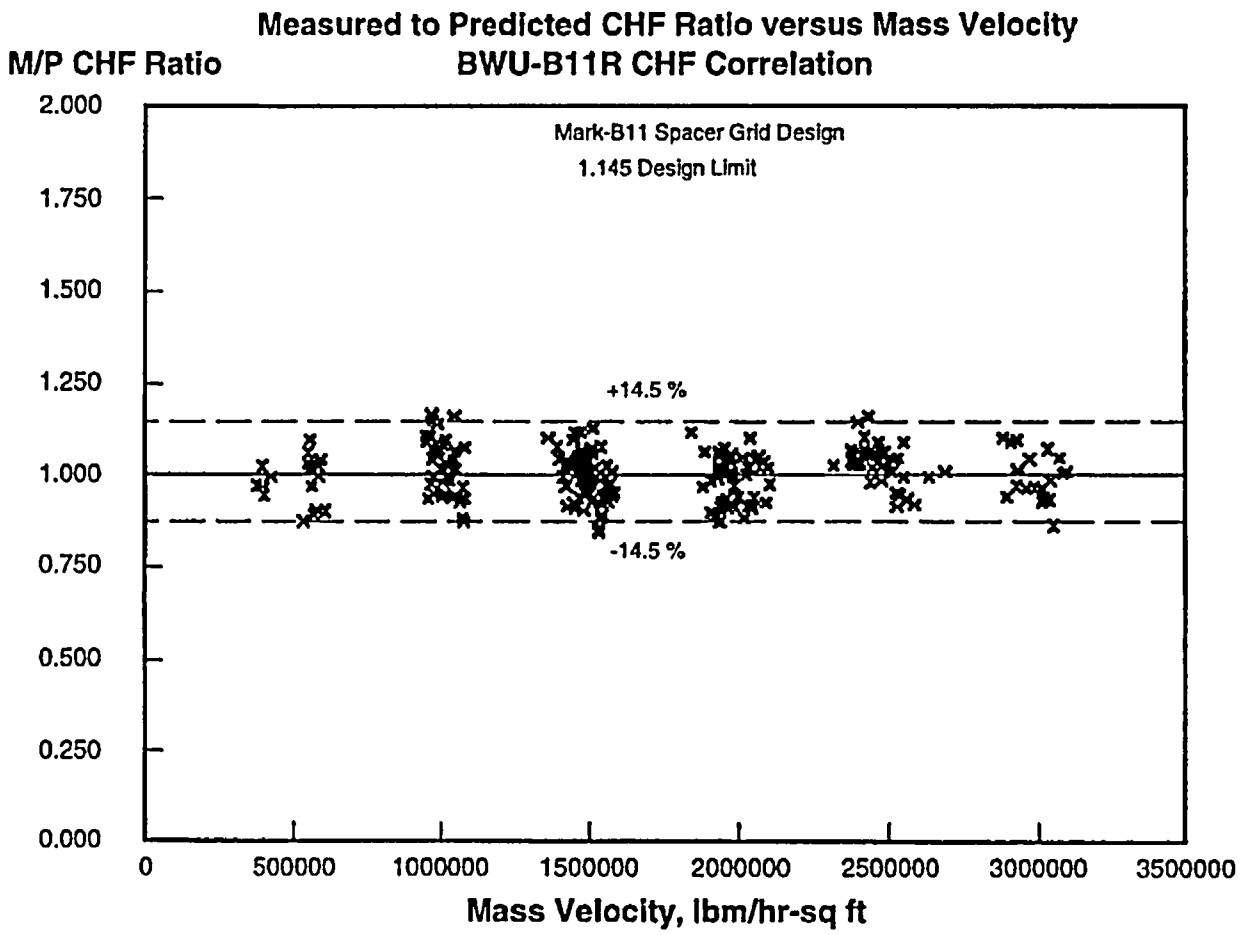


Figure I-2



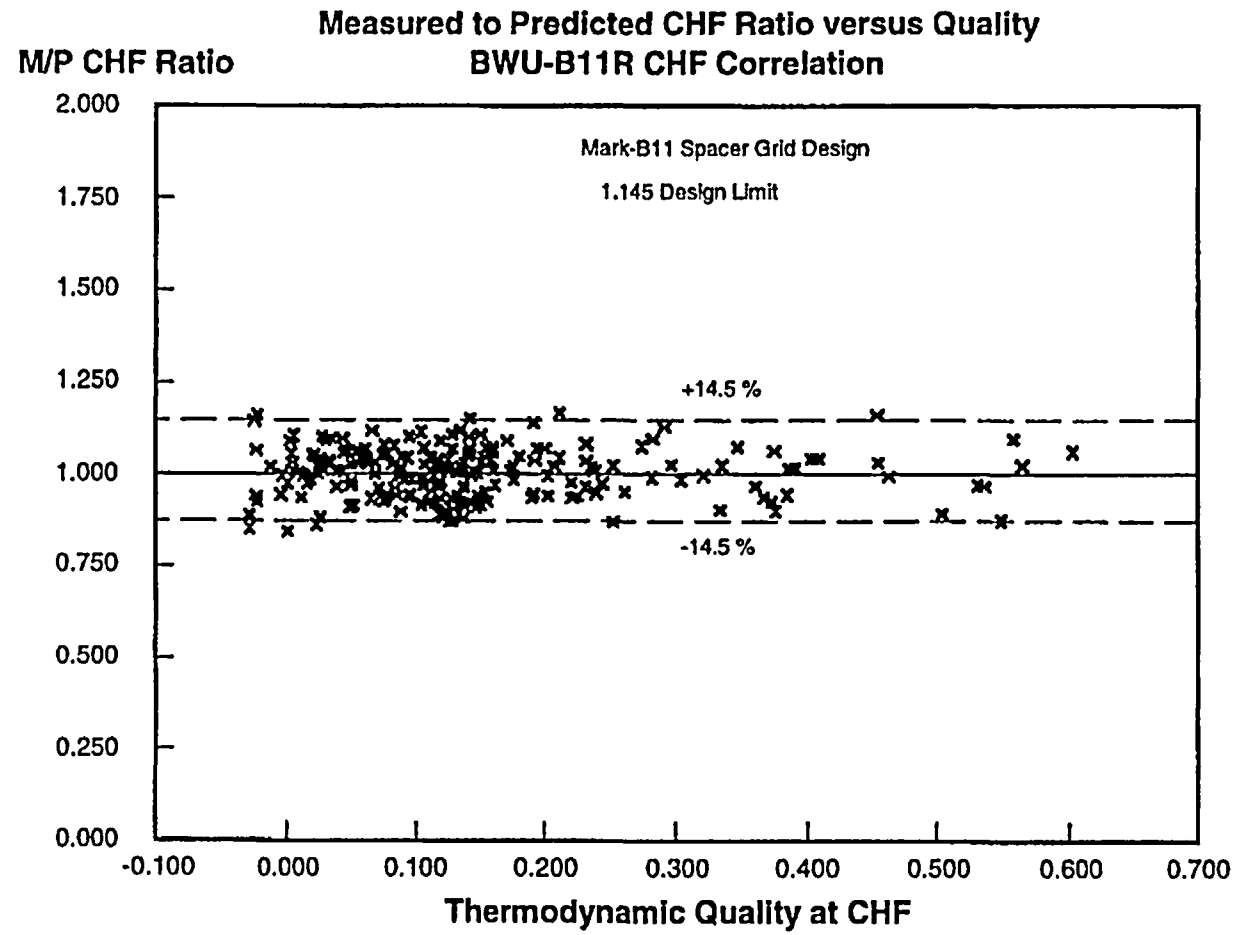


Figure I-3

Figure 14

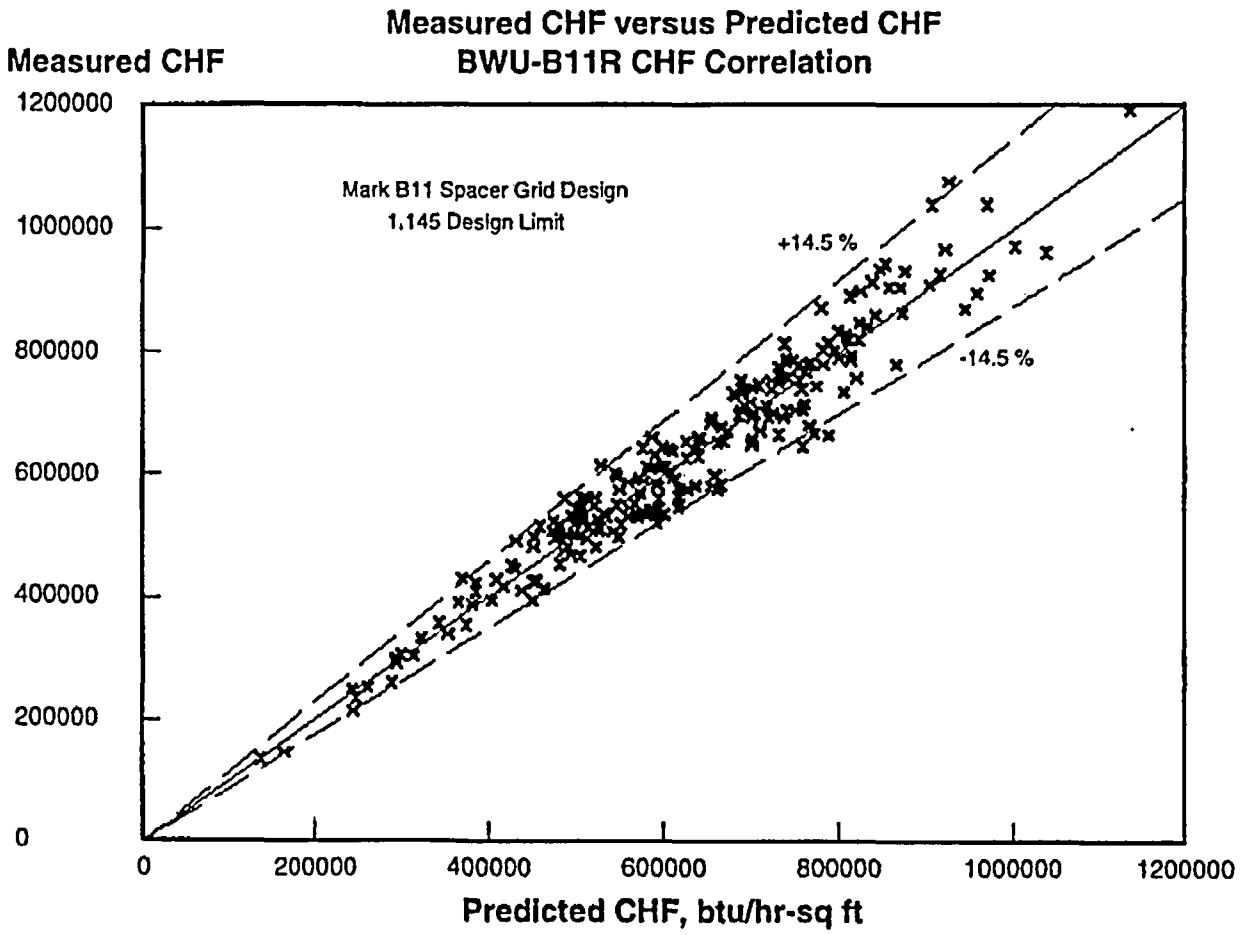


Figure I-5

Histogram of Measured to Predicted CHF Ratios
BWU-B11R CHF Correlation

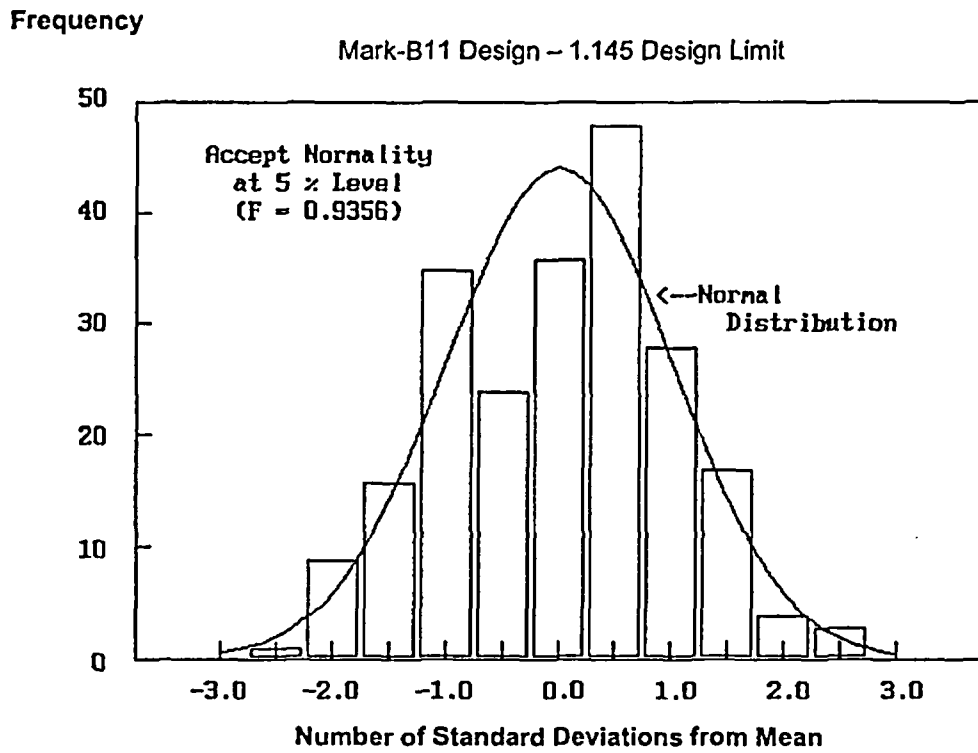


Table I-1
 Measured to Predicted Results by Test Section

Test Section	Data	Avg M/P	Standard Deviation	Max M/P	Min M/P	Coefficient of Variation
Test 26.0 (U/C)	32	1.0306	0.0596	1.139	0.899	0.058
Test 27.1 (G/T)	26	0.9968	0.0589	1.070	0.873	0.059
Test 28.0 (U/C)	63	1.0089	0.0712	1.165	0.842	0.071
Test 29.0 (C/U)	63	0.9635	0.0526	1.097	0.863	0.055
Test 30.0 (G/T)	37	1.0365	0.0676	1.161	0.870	0.065
BWU-B11R	221	1.0023	0.0679	1.165	0.842	0.068

Geometry: U/C = Unit Cell, G/T = Guide Tube, C/U = Cold Unit

Table I-2
 Measured to Predicted Results by Mass Velocities

Mass Velocity Mlbm/hr-ft ²	Data	Avg M/P	Standard Deviation	Max M/P	Min M/P	Coefficient of Variation
Below 0.75	17	0.9821	0.0640	1.097	0.872	0.065
0.75 to 1.25	39	1.0229	0.0766	1.165	0.872	0.075
1.25 to 1.75	62	0.9958	0.0659	1.128	0.842	0.066
1.75 to 2.25	48	0.9850	0.0656	1.117	0.870	0.067
2.25 to 2.75	35	1.0299	0.0562	1.161	0.915	0.055
2.75 to 3.25	20	0.9926	0.0659	1.102	0.863	0.066
BWU-B11R	221	1.0023	0.0679	1.165	0.842	0.068

-0.1 % Slope (bias), ANOVA:F = 3.138 (5/215 df) - Fcrit = 2.255

Table I-3
 Measured to Predicted Results by Pressures

Pressure psia	Data	Avg M/P	Standard Deviation	Max M/P	Min M/P	Coefficient of Variation
Below 375	3	0.9828	0.0561	1.037	0.925	0.057
375 to 900	14	0.9962	0.0609	1.071	0.872	0.061
900 to 1250	15	1.0287	0.0734	1.161	0.920	0.071
1250 to 1650	40	0.9942	0.0708	1.165	0.870	0.071
1650 to 1950	44	0.9991	0.0673	1.161	0.883	0.067
1950 to 2250	55	1.0078	0.0682	1.148	0.842	0.068
Above 2250	50	1.0005	0.0680	1.118	0.851	0.068
BWU-B11R	221	1.0023	0.0679	1.165	0.842	0.068

0.1 % Slope (bias), ANOVA:F = 0.609 (6/214 df) - Fcrit = 2.139

Table I-4
 Measured to Predicted Results by Quality

Quality	Data	Avg M/P	Standard Deviation	Max M/P	Min M/P	Coefficient of Variation
-.05 to .05	47	1.0082	0.0739	1.161	0.842	0.073
.05 to .15	102	0.9942	0.0655	1.148	0.870	0.066
.15 to .25	39	1.0167	0.0612	1.165	0.915	0.060
.25 to .35	13	1.0114	0.0739	1.128	0.872	0.073
.35 to .45	10	0.9850	0.0578	1.062	0.899	0.059
.45 to .55	7	0.9836	0.0957	1.161	0.872	0.097
.55 to .65	3	1.0602	0.0368	1.097	1.023	0.035
BWU-B11R	221	1.0023	0.0679	1.165	0.842	0.068

0.0 % Slope (bias), ANOVA: F = 1.203 (6/214 df) - Fcrit = 2.139

Table I-5
 BWU-B11R Uniform Coefficients (A1 – A14)



Note that with the above coefficients the resulting uniform CHF must be exponentiated.
 (i.e. $Q_{calc} = EXP(Q_{calc})$).

The standard BWU-Z FLS and F-Factor coefficients apply (Table 3-1 page 3-5 of Reference 1).

The full form of the BWU CHF correlation is detailed on pages 1-4 and 1-5 of Reference 1.

Table I-6
 BWU-B11R Range of Applicability

Pressure, psia	315 to 2425
Mass Velocity, Mlb/hr-ft ²	0.377 to 3.095
Quality at CHF	less than 0.6025
Spacer Grid	Framatome ANP Mark-B11
Design Limit DNBR	1.145
Analysis Code	LYNXT
Correlation Coefficients	Table I-5 (above)

Table I-7
Individual Measured To Predicted Results

ID	AFS Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Zchf	F Fact
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Types: 1 Large Pin Unit, 3 Large Pin Guide Tube, 0 Large Pin Cold Unit
Units: Measured CHF - btu/hr-sq ft, Mass Velocity - lbm/hr-sq ft
Press - psia, Zchf - inches, AFS 11 = 1.55 Cosine

Table I-7 (Continued)
Individual Measured To Predicted Results

ID	AFS Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Zchf	F Fact
[Empty Table Body]								

Types: 1 Large Pin Unit, 3 Large Pin Guide Tube, 0 Large Pin Cold Unit
Units: Measured CHF - btu/hr-sq ft, Mass Velocity - lbm/hr-sq ft
Press - psia, Zchf - inches, AFS 11 = 1.55 Cosine

Table I-7 (Continued)
Individual Measured To Predicted Results

ID	AFS Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Zchf	F Fact
[Empty Table Body]								

Types: 1 Large Pin Unit, 3 Large Pin Guide Tube, 0 Large Pin Cold Unit
Units: Measured CHF - btu/hr-sq ft, Mass Velocity - lbm/hr-sq ft
Press - psia, Zchf - inches, AFS 11 = 1.55 Cosine

Table I-7 (Continued)
Individual Measured To Predicted Results

ID	AFS Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Zchf	F Fact
[Empty Table Body]								

Types: 1 Large Pin Unit, 3 Large Pin Guide Tube, 0 Large Pin Cold Unit
Units: Measured CHF - btu/hr-sq ft, Mass Velocity - lbm/hr-sq ft
Press - psia, Zchf - inches, AFS 11 = 1.55 Cosine

Table I-7 (Continued)
Individual Measured To Predicted Results

ID	AFS Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Zchf	F Fact
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The following data point was the sole outlier for the BWU-B11R Correlation

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Types: 1 Large Pin Unit, 3 Large Pin Guide Tube, 0 Large Pin Cold Unit
Units: Measured CHF - btu/hr-sq ft, Mass Velocity - lbm/hr-sq ft
Press - psia, Zchf - inches, AFS 11 = 1.55 Cosine