Appendix F

Application of the BWU-Z CHF Correlation
to the Mark BW17 Fuel Design
with Mid-Span-Mixing Grids

Introduction

In 1992, FCF (then BWFC) conducted a series of tests at the Columbia University Heat Transfer Research Facility (HTRF) to qualify the Critical Heat Flux (CHF) capability of the Mark BW17 spacer grid design. In all, 12 tests representing 7 different geometrical configurations were conducted. All of these multipoint tests except for one utilized an axial grid spacing (pitch) of 20.5 inches with standard 2.25 inch length mixing vane grids. One test contained "mid-span-mixing" (MSM) grids placed in the middle of the spans 4, 5 and 6 (of 7 total). These MSM grids had the standard Mark BW17 mixing vane geometry, but were only about a half an inch in height.

Reference F-1 of this appendix used the local condition results of the Mark BWl7 testing program with the existing BWCMV CHF correlation [F-2] to qualify both the standard and MSM configurations. In BAW 10199 [F-3], a new CHF correlation form (the BWU correlation, Section 1.4) was developed and a separate version was qualified for use with three different grid designs. The version qualified for use with the Mark BWl7 design is termed BWU-Z. BWU-Z was qualified for the Mark BWl7 grid with a 20.5 inch pitch (Table 4-1). As was shown in Reference F-l, the addition of MSM grids to the standard grid configuration substantially increases the CHF capability of the resulting configuration. It is the purpose of this document to quantify (in the form of a multiplier on BWU-Z) the increase in CHF capability for the Mark BWl7 design with MSM grids.

For the purposes of this qualification, FCF conducted a second MSM test (FCF 43.0) with the guide tube cross-sectional geometry. The geometry of FCF 43.0 (FCF43) is exactly the same as tests BW 18.0 and BW 18.1 (BW18) except for the guide tube.

Test FCF43 was conducted 1) to show that guide tube MSM grid CHF performance was equivalent to unit cell performance, and 2) to extend the MSM data base to low pressures and low flows. (A high flow, high pressure point is one with a nominal flow greater than or equal to 1.0 million pounds per hour per square foot <u>and</u> a nominal pressure greater than or equal to 1500 psia. All other data are low flow, low pressure.)

Test Description

All of the Mark BW17 CHF tests were performed at the Columbia University HTRF. The HTRF is a ten megawatt electric facility capable of testing full length (12 foot) rod arrays in up to a 6 by 6 matrix. HTRF testing conditions cover the full range of PWR operating conditions with pressures up to 2500 psia, mass velocities up to 3.5 million pounds per hour per square foot and inlet temperatures approaching saturation. A detailed description of the Columbia HTRF is provided in Reference F-4.

Individual CHF tests for the Mark BW17 design are summarized in Table F-1. Complete information, including shroud dimensions, power peaking information, form loss coefficients, is provided in Reference F-1.

Data Analysis

The bundle and cell geometry, the rod radial peaking values, the heater rod axial flux shape, the types, axial locations and form losses of spacer grids, and the thermocouple locations comprise the mathematical model for each separate test section. The data from each CHF observation within a test consists of the variables of test section power, flow, inlet temperature, pressure and CHF location (rod and axial location) and together define a data point.

Each test section is modeled for analysis with the LYNXT thermal-hydraulic computer code [F-5]. For each set of bundle data, LYNXT produces the local thermal-hydraulic conditions (mass velocity, thermodynamic quality, heat flux, etc.) The local condition results along with the test section global variables can then be analyzed against an existing CHF correlation or used to obtain optimized coefficients (a new correlation).

Method

The data analysis will be in two parts: 1) compare the common (duplicate) data in each test to show that they match, and 2) determine the MSM multiplier as follows:

Use the local conditions data from the MSM tests of Table F-1 with the BWU-Z correlation to obtain an MSM multiplier for the MSM configuration. The Design Limit DNBR for the MSM configuration is then shown to be less than or equal to the 1.19 value qualified in Table 4-1 of BAW 10199 [F-3] for the standard Mark BWl7 design spaced at 20.5 inches. Additionally, the final mean M/P CHF ratio (with the MSM multiplier) must be shown to be greater than or equal to 1.0. These dual criteria insure conservatism of the application.

The applicable correlation is then

$$(Q_{chf})_{msm} = F_{msm} * FLS * Q_{unif} / F$$

where Q_{unif}, FLS and F are the original BWU-Z factors from BAW 10199 [F-3] and F_{msm} is determined in this analysis.

Analysis Results

Test FCF18 achieved 76 total CHF data. Of these, 73 were high flow, high pressure data and 3 low flow, low pressure data. Test FCF43 achieved 72 total CHF data. Of these, 53 were high flow, high pressure data and 19 low flow, low pressure data. There were 52 common points (i.e., the same inlet temperature, mass velocity and pressure) between the tests).

An analysis of common points with the unmodified BWU-Z correlation yields:

Test	Data	Mean M/P CHF	Std Deviation
FCF18	52	1.211	.131
FCF43	52	1.194	.098
MSM Data	104	1.203	.115

A one way Analysis of Variance (ANOVA)[F-7] with 1 and 102 degrees of freedom results in an F statistic of 0.579. The critical F value at the .05 level of confidence is 3.934.

This shows that there is no statistical difference in the test results.

Next, the local conditions analysis was performed with all the data as explained above to iterate to an F_{msm} value of 1.182. For this analysis, F_{msm} will be conservatively rounded to 1.180. The applicable results are documented in Tables F-2 and F-3 and presented graphically in Figures F-1 through F-4. The resulting design limit using the statistics shown in Table F-2 is

t, # of tests	2
n, # of data	148
N, degrees of freedom (n-1)	147
M/P, avg measured to predicted CHF	1.0138
S(M/P,N)	0.0920
K (147,0.95,0.95), one sided tolerance factor [F-6]	1.872

DNBR(L) = 1 / (M/P – K*S)

= 1 / [1.0138 - 1.872(.0920)] = 1.1882 < 1.190

Application

It has been shown that the CHF performance of the Mark BW17 design with MSM grids between the top 4 standard Mark BW17 grids (spans 4, 5 and 6) can be described with a simple modification to the BWU-Z correlation.

$$(Q_{chf})_{msm} = F_{msm} * FLS * Q_{unif} / F$$

where F_{msm} = 1.180. FLS, Q_{unif} and F are as defined for BWU-Z in Table 3-1 of BAW 10199 [F-3], with a grid spacing of 20.5 inches, and ranges of applicability as specified in Table 4-1 (also of BAW 10199).

For the analysis of grid spans not containing MSM grids, F_{msm} = 1.0 (i.e. no enhancement factor is applied). For the uppermost span, in which the end of heated length (EOHL) occurs less than one grid span beyond the last mixing grid, the effective grid spacing (distance from the last grid to the EOHL) is input rather than the 20.5 inch spacing factor.

References

F-1. D. A. Farnsworth and G. A. Meyer, "CHF Testing and Analysis of the Mark-BW Fuel Assembly Design," BAW-10189P-A, Babcock & Wilcox, January, 1996.

F-2. D. A. Farnsworth and G. A. Meyer, "BWCMV Correlation of Critical Heat Flux in Mixing Vane Grid Fuel Assemblies", BAW-10159P, Babcock & Wilcox, July, 1990.

F-3. D. A. Farnsworth and G. A. Meyer, "The BWU Critical Heat Flux Correlations," BAW-10199P-A, Framatome Cogema Fuels, August 1996.

F-4. C. F. Fighetti and D.G. Reddy, "Parametric Study of CHF Data," EPRI-NP-2609, 1982 (Volume 1 of 3).

F-5. J. H. Jones, K.J. Firth, J. R. Gloudemans and J. M. Alcorn, "LYNXT Core Transient Thermal-Hydraulic Program," BAW-10156-A, Rev. l, B&W Fuel Company, August, 1993.

F-6. D. B. Owens, "Factors for One-Sided Tolerance Limits," Sandia Corporation Monograph, 1963.

F-7. Bernard Ostle, Statistics in Research, 2nd Edition, The Iowa State University Press, 1963.

Figure F-1 - Mid-Span-Minxing Grid
Measured to Predicted CHF versus Mass Velocity

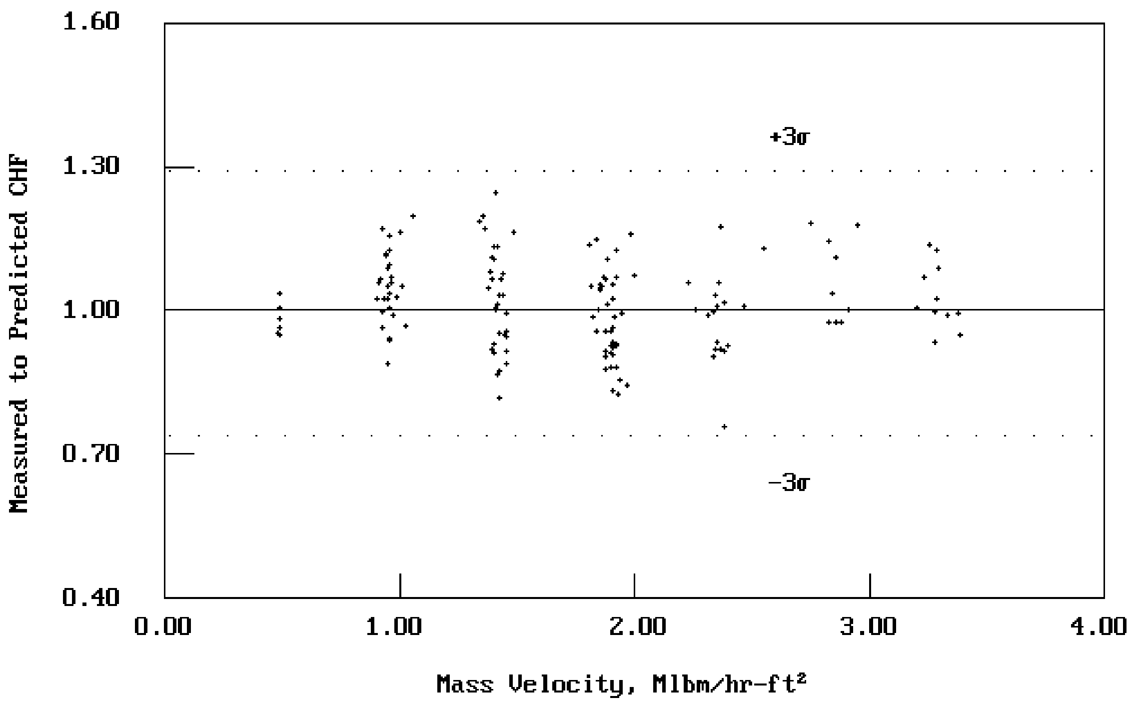

Figure F-2 - Mid-Span-Mixing Grid
Measured to Predicted CHF versus Quality

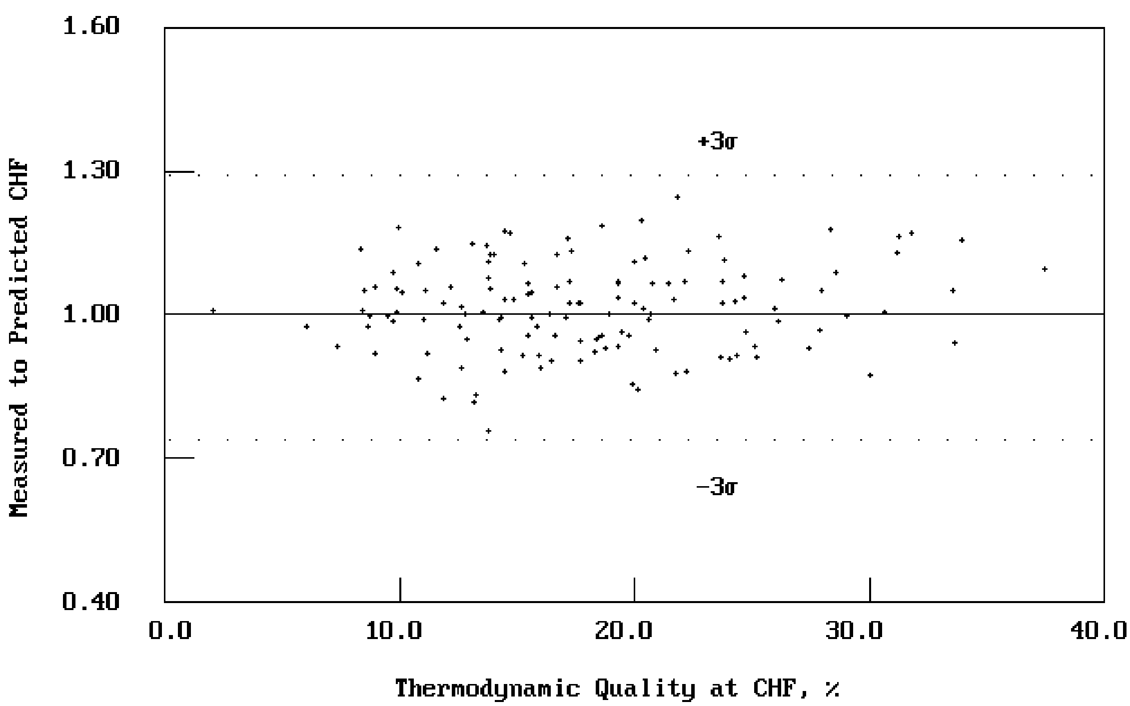

Figure F-3 - Mid-Span-Mixing Gird
Measured to Predicted CHF versus Pressure

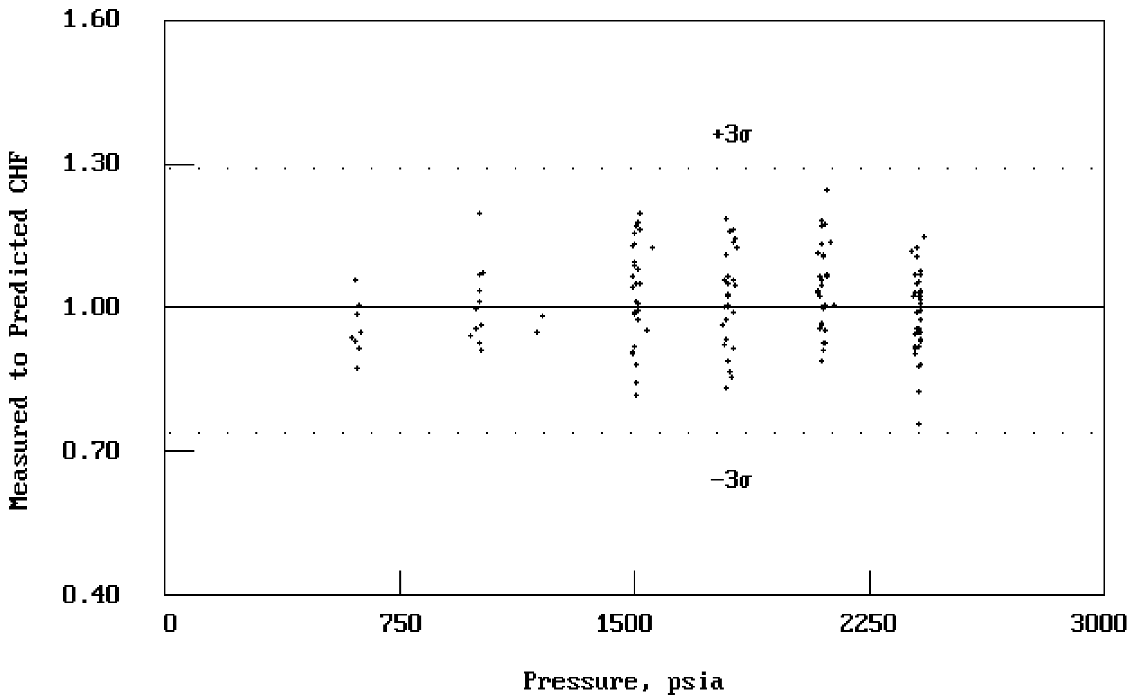

Figure F-4 - Mid-Span-Mixing Grid
M/P CHF - Accept Normality at 5% LEVEL

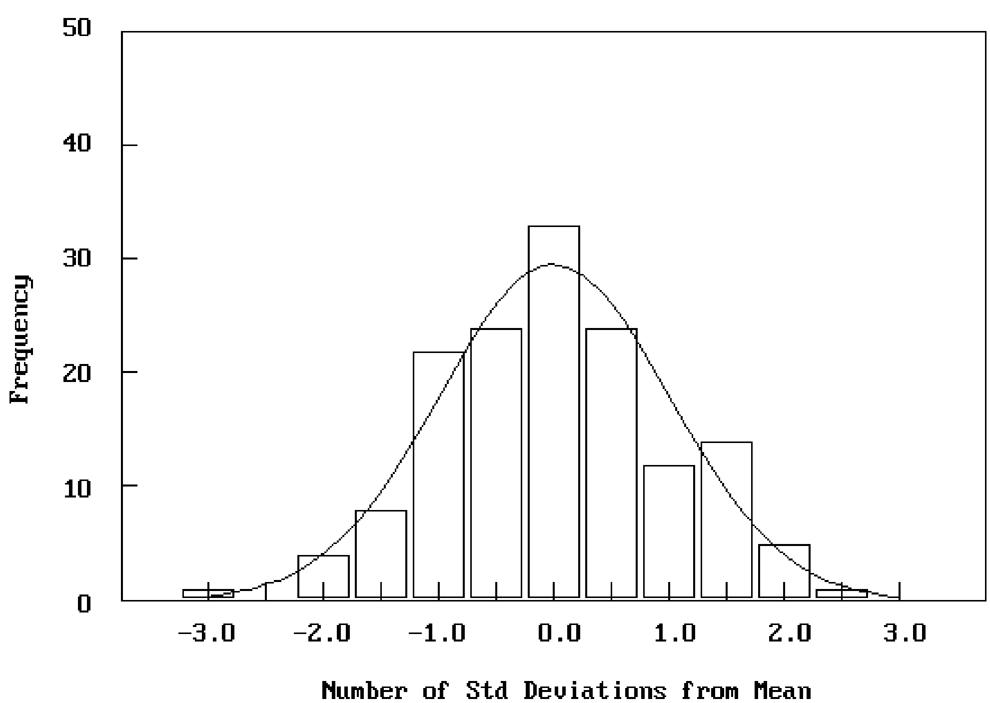

Table F-1

Mark BWl7 CHF Test Summary

Test	Type [1]	Matrix	AFS [2]	Pin OD inch	Pitch inch	G/T OD inch	Heated Length inches	Grid Spacing inches
BW 12.0	Unit	5x5	1.55 Sym	.374	.422	---	143.4	20.5
BW 13.1	Unit	5x5	1.55 Sym	.374	.422	---	143.4	20.5
BW 14.1	G-T	5x5	1.55 Sym	.374	.422	.482	143.4	20.5
BW 15.1	C-U	5x5	1.55 Sym	.374	.422	- -	143.4	20.5
BW 16.0	C-R	5x5	1.55 Sym	.374	.422	---	143.4	20.5
BW 17.0	[3]W-H	5x5	1.55 Sym	.374	.422	- -	143.4	20.5
BW 18.0	[3]MSM	5x5	1.55 Sym	.374	.422	---	143.4	[4]20.5
BW 18.1	[3]MSM	5x5	1.55 Sym	.374	.422	---	143.4	[4]20.5
BW 19.0	G-T	5x5	1.55 Sym	.374	.422	.482	143.4	20.5
BW 20.0	SLB	5x5	1.55 Sym	.374	.422	---	143.4	20.5
BW 43.0	[3]MSM GT	5x5	1.55 Sym	.374	.422	.482	143.4	[4]20.5

[1] - G-T = Guide Tube, C-U = Cold Unit, C-R = Cold Row, Int = Intersection
MSM = Mid-Span-Mixer, SLB = Steam Line Break Conditions
[2) - Sym = Symmetric, Out = Outlet
[3] - Not in BWU-Z database
[4) - There are 7 grid spans (#1 at bottom, #7 at top). Non-structural mixing grids are positioned at the middle of spans 4, 5 and 6. Structural grids are spaced at 20.5 inches.

Table F-2

M/P CHF Results with F_{msm} = 1.180

Data in this Analysis	148
Mean M/P CHF Ratio	1.0138
Std Dev / Coef Var	0.0920 / 0.0907
Min / Max Values	0.7672 / 1.2409
Des Limit / Normality	1.188 / Accept
Data Out by Range, Outlier	0 / 0
CWF/Fmsm/Grid Ht	1.000/1.180/2.250
Mass Vel Range	0.471 to 3.385
Quality Range	-.0195 to .6797
Pressure Range	594 to 2425
BWU Correlation	Table 3-1

------------------Grouped by Mass Velocities----------------------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
0.5 Mass Vel						
1.0 Mass Vel						
1.5 Mass Vel						
2.0 Mass Vel			b,c,d			
2.5 Mass Vel						
3.0 Mass Vel						
3.5 Mass Vel						
All Mass Vel	148	1.0138	0.0920	1.241	0.767	0.091

---------------------Grouped by Pressures----------------------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
375 to 900						
900 to 1250						
1250 to 1650						
1650 to 1950			b,c,d			
1950 to 2250						
2250 to 3200						
All Pressures	148	1.0138	0.0920	1.241	0.767	0.091

---------------------Grouped by - Qualities--------------------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
Below 5% X						
5% to 10% X						
10% to 15% X						
15% to 20% X			b,c,d			
20% to 25% X						
25% to 30% X						
Above 30% X						
All Qualities	148	1.0138	0.0920	1.241	0.767	0.091

Table F-3

M/P CHF Results with F_{msm} = 1.180
Individual Results

ID	AFS	Type	M/P CHF	Meas CHF	Press	Mass Vel	Quality	Z chf	F Fact
43014	11	4							
43015	11	4							
43016	11	4							
43017	11	4							
43021	11	4							
43022	11	4							
43023	11	4							
43024	11	4							
43025	11	4							
43026	11	4							
43027	11	4							
43028	11	4							
43029	11	4							
43030	11	4							
43031	11	4							
43032	11	4							
43033	11	4							
43034	11	4							
43035	11	4							
43036	11	4							
43037	11	4							
43038	11	4							
43039	11	4							
43040	11	4							
43041	11	4							
43042	11	4							
43043	11	4							
43044	11	4							
43045	11	4							
43046	11	4							
43047	11	4			b,c,d				
43048	11	4							
43049	11	4							
43050	11	4							
43051	11	4							
43052	11	4							
43053	11	4							
43054	11	4							
43055	11	4							
43056	11	4							
43057	11	4							
43058	11	4							
43063	11	4							
43064	11	4							
43065	11	4							
43066	11	4							
43067	11	4							
43068	11	4							
43069	11	4							
43070	11	4							
43071	11	4							
43072	11	4							
43073	11	4							
43074	11	4							
43075	11	4							
43076	11	4							

43077	11	4
43078	11	4
43079	11	4
43080	11	4
43081	11	4
43082	11	4
43083	11	4
43084	11	4
43085	11	4
43086	11	4
43087	11	4
43088	11	4
43089	11	4
43090	11	4
43091	11	4
43092	11	4
18001	11	1
18002	11	1
18103	11	1
18004	11	1
18005	11	1
18006	11	1
18007	11	1
18008	11	1
18009	11	1
18010	11	1
18011	11	1
18012	11	1
18013	11	1
18014	11	1
18015	11	1
18016	11	1
18017	11	1
18018	11	1
18119	11	1
18120	11	1
18121	11	1
18122	11	1
18123	11	1
18124	11	1
18125	11	1
18126	11	1
18127	11	1
18128	11	1
18129	11	1
18130	11	1
18131	11	1
18132	11	1
18133	11	1
18134	11	1
18135	11	1
18136	11	1
18137	11	1
18138	11	1
18139	11	1
18140	11	1
18141	11	1
18142	11	1
18143	11	1
18144	11	1
18145	11	1
18146	11	1

b,c,d

18147	11	1	
18148	11	1	
18149	11	1	
18150	11	1	
18151	11	1	
18152	11	1	
18153	11	1	
18154	11	1	
18155	11	1	
18156	11	1	
18157	11	1	
18158	11	1	
18159	11	1	
18160	11	1	
18161	11	1	b,c,d
18162	11	1	
18163	11	1	
18164	11	1	
18165	11	1	
18166	11	1	
18167	11	1	
18168	11	1	
18169	11	1	
18170	11	1	
18171	11	1	
18172	11	1	
18173	11	1	
18174	11	1	
18175	11	1	
18176	11	1	