FRAMATOME COGEMA FUELS

December 6, 2000
GR00-186.doc

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Subject: Submittal of Topical Report BAW-10199P, Addendum 1, "The BWU Critical Heat flux Correlations," December 2000.

Gentlemen:

Enclosed are fifteen (15) copies of Topical Report BAW-10199P-A, Addendum 1 and twelve (12) copies of Topical Report BAW-10199-A, Addendum 1. These reports will serve as the accepted versions, proprietary and non-proprietary, of BAW-10199P-A, Addendum 1 which was recently reviewed and found to be acceptable by the NRC staff. This report justifies the application of the BWU-Z CHF correlation to fuel assemblies with the Mark-B11 spacer grid design.

Copies of the NRC acceptance letter and accompanying SER are included between the title page and the table of contents of Addendum 1 of the report. Copies of responses to the NRC requests for additional information are included as Appendices G and H of the report.

In accordance with 10 CFR 2.790, FCF requests that BAW-10199P-A, Addendum 1 be considered proprietary and withheld from public disclosure. An affidavit supporting this request is attached.

Very truly yours,

TAColeman

T. A. Coleman, Vice President
Government Relations

cc: J. S. Wermiel, NRC
T. L. Huang, NRC
S. N. Bailey, NRC
C. E. Beyer, PNL
20A13 File/Records Management

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FRAMATOME TECHNOLOGIES

Framatome Cogema Fuels
3315 Old Forest Road, P.O. Box 10935, Lynchburg, VA 24506-0935
Telephone: 804-832-3000 Fax: 804-832-3663

bcc: J. B. Andrews
G. A. Meyer
A. B. Copsey
D. A. Farnsworth
M. E. Aldrich
C. F. McPhatter
R. D. Williamson
W. E. Van Scooter

AFFIDAVIT OF THOMAS A. COLEMAN

A. My name is Thomas A. Coleman. I am Vice President of Government Relations for Framatome Cogema Fuels (FCF). Therefore, I am authorized to execute this Affidavit.

B. I am familiar with the criteria applied by FCF to determine whether certain information of FCF is proprietary and I am familiar with the procedures established within FCF to ensure the proper application of these criteria.

C. In determining whether an FCF document is to be classified as proprietary information, an initial determination is made by the Unit Manager, who is responsible for originating the document, as to whether it falls within the criteria set forth in Paragraph D hereof. If the information falls within any one of these criteria, it is classified as proprietary by the originating Unit Manager. This initial determination is reviewed by the cognizant Section Manager. If the document is designated as proprietary, it is reviewed again by personnel and other management within FCF as designated by the Vice President of Government Relations to assure that the regulatory requirements of 10 CFR Section 2.790 are met.

D. The following information is provided to demonstrate that the provisions of 10 CFR Section 2.790 of the Commission's regulations have been considered:

(i) The information has been held in confidence by FCF. Copies of the document are clearly identified as proprietary. In addition, whenever FCF transmits the information to a customer, customer's agent, potential customer or regulatory agency, the transmittal requests the recipient to hold the information as proprietary. Also, in order to strictly limit any potential or actual customer's use of proprietary information, the substance of the following provision is included in all agreements entered into by FCF, and an equivalent version of the proprietary provision is included in all of FCF's proposals:

"Any proprietary information concerning Company's or its Supplier's products or manufacturing processes which is so designated by Company or its Suppliers and disclosed to Purchaser incident to the performance of such contract shall remain the property of Company or its Suppliers and is disclosed in confidence, and Purchaser shall not publish or otherwise disclose it to others without the written approval of Company, and no rights, implied or otherwise, are granted to produce or have produced any products or to practice or cause to be practiced any manufacturing processes covered thereby.

Notwithstanding the above, Purchaser may provide the NRC or any other regulatory agency with any such proprietary information as the NRC or such other agency may require; provided, however, that Purchaser shall first give Company written notice of such proposed disclosure and Company shall have the right to amend such proprietary information so as to make it non-proprietary. In the event that Company cannot amend such proprietary information, Purchaser shall, prior to disclosing such information, use its best efforts to obtain a commitment from NRC or such other agency to have such information withheld from public inspection.

Company shall be given the right to participate in pursuit of such confidential treatment."

(ii) The following criteria are customarily applied by FCF in a rational decision process to determine whether the information should be classified as proprietary. Information may be classified as proprietary if one or more of the following criteria are met:

a. Information reveals cost or price information, commercial strategies, production capabilities, or budget levels of FCF, its customers or suppliers.

b. The information reveals data or material concerning FCF research or development plans or programs of present or potential competitive advantage to FCF.

c. The use of the information by a competitor would decrease his expenditures, in time or resources, in designing, producing or marketing a similar product.

d. The information consists of test data or other similar data concerning a process, method or component, the application of which results in a competitive advantage to FCF.

e. The information reveals special aspects of a process, method, component or the like, the exclusive use of which results in a competitive advantage to FCF.

f. The information contains ideas for which patent protection may be sought.

The document(s) listed on Exhibit "A", which is attached hereto and made a part hereof, has been evaluated in accordance with normal FCF procedures with respect to classification and has been found to contain information which falls within one or more of the criteria enumerated above. Exhibit "B", which is attached hereto and made a part hereof, specifically identifies the criteria applicable to the document(s) listed in Exhibit "A".

(iii) The document(s) listed in Exhibit "A", which has been made available to the United States Nuclear Regulatory Commission was made available in confidence with a request that the document(s) and the information contained therein be withheld from public disclosure.

(iv) The information is not available in the open literature and to the best of our knowledge is not known by Combustion Engineering, Siemens, General Electric, Westinghouse or other current or potential domestic or foreign competitors of Framatome Cogema Fuels.

(v) Specific information with regard to whether public disclosure of the information is likely to cause harm to the competitive position of FCF, taking into account the value of the information to FCF; the amount of effort or money expended by FCF developing the information; and the ease or difficulty with which the information could be properly duplicated by others is given in Exhibit "B".

E. I have personally reviewed the document(s) listed on Exhibit "A" and have found that it is considered proprietary by FCF because it contains information which falls within one or more of the criteria enumerated in Paragraph D, and it is information which is customarily held in confidence and protected as proprietary information by FCF. This report comprises information utilized by FCF in its business which afford FCF an opportunity to obtain a

competitive advantage over those who may wish to know or use the information contained in the document(s).

TAColeman

THOMAS A. COLEMAN

State of Virginia)
) SS. Lynchburg
City of Lynchburg)

Thomas A. Coleman, being duly sworn, on his oath deposes and says that he is the person who subscribed his name to the foregoing statement, and that the matters and facts set forth in the statement are true.

TAColeman

THOMAS A. COLEMAN

Subscribed and sworn before me
this 7th day of December 2000.

Wanda L. Wade
Notary Public in and for the City
of Lynchburg, State of Virginia.

My Commission Expires 8/31/01

EXHIBITS A & B

EXHIBIT A

BAW-10199P, Addendum 1, "The BWU Critical Heat Flux Correlations."

EXHIBIT B

The above listed document contains information which is considered Proprietary in accordance with Criteria c, d, and e of the attached affidavit.

BAW-10199-A
Addendum 1
December 2000

The BWU Critical Heat Flux Correlations

FRAMATOME COGEMA FUELS

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Addendum 1 to BAW-10199P-A

The BWU Critical Heat Flux Equations

Applications to the Mark B11 and Mark BW17 MSM Designs

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001
April 6, 2000

Mr. T. A. Coleman, Vice President
Government Relations
Framatome Cogema Fuels
3315 Old Forest Road
P.O. Box 10935
Lynchburg, VA 24506-3663

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT BAW-10199P, ADDENDUM 1, "THE BWU CRITICAL HEAT FLUX CORRELATIONS" (TAC NO. M96728)

Dear Mr. Coleman:

The U.S. Nuclear Regulatory Commission (NRC) staff has completed its review of the subject topical report, which was submitted by Framatome Cogema Fuels (FCF), by letter dated September 30, 1996. The staff has found that this report is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the report and the associated NRC safety evaluation, which is enclosed. The safety evaluation defines the bases for acceptance of the report. The staff will not repeat its review of the matters described in BAW-10199P, Addendum 1, when the report appears as a reference in license applications, except to ensure that the material presented applies to the specific plant involved.

In accordance with procedures established in NUREG-0390, the NRC requests that the B&WOG publish accepted versions of the submittal, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed safety evaluation between the title page and the abstract, and an -A (designating accepted) following the report identification symbol. The accepted version shall also incorporate all communications between FCF and the NRC during this review.

Pursuant to 10 CFR 2.790, the staff has determined that the enclosed safety evaluation does not contain proprietary information. However, the staff will delay placing the safety evaluation in the public document room for 10 calendar days from the date of this letter to allow you the opportunity to comment on the proprietary aspects only. If, after that time, you do not request that all or portions of the safety evaluation be withheld from public disclosure in accordance with 10 CFR 2.790, the safety evaluation will be placed in the NRC Public Document Room.

Should our acceptance criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, applicants referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the topical report without revision of the respective documentation.

Should you have any questions or wish further clarification, please call Stewart Bailey at (301) 415-1321.

Sincerely,

Stuart A. Richards, Director
Project Directorate IV & Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 693

Enclosure: Safety Evaluation

cc w/encl: See next page

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10199P, ADDENDUM 1

"THE BWU CRITICAL HEAT FLUX CORRELATIONS"

FRAMATOME COGEMA FUELS

1.0 INTRODUCTION

By letter dated September 30, 1996 (Reference 1), Framatome Cogema Fuels (FCF) submitted Addendum 1 to Topical Report BAW-10199P, "The BWU Critical Heat Flux Correlations." The purpose of the submittal is to extend the application of the BWU-Z critical heat flux (CHF) correlation to fuel with the Mark-B11 spacer grid design and to the Mark-BW17 fuel with mid-span-mixing (MSM) grids. The BWU-Z CHF correlation is one of the approved CHF correlations in BAW-10199P-A (Reference 2) for Mark-BW17 mixing vane fuel design.

The NRC staff was assisted in this review by its consultant, Pacific Northwest National Laboratory, in relation to the application of this topical report to Duke Power Company's Oconee Nuclear Station. The attached Technical Evaluation Report provides our consultant's detailed evaluation and findings.

The NRC staff evaluated the subject topical report and FCF's responses to staff's requests for additional information (RAIs) dated February 23, 1998, (Reference 3) and October 21, 1998 (Reference 4). There were also several conference calls related to the application of BWU-Z to the Mark-BW17 fuel with MSM grids. In order to support the immediate needs of FCF's customers, and as requested by FCF's letter dated December 16, 1999 (Reference 5), this safety evaluation only discusses the application of BWU-Z to fuel with the Mark-B11 spacer grid design. The staff will continue its review of the applicability to Mark-BW fuel with MSM grids at a later date.

2.0 EVALUATION

The staff reviewed extending the use of the approved BWU-Z CHF correlation to the Mark-B11 spacer grid design. The BWU-Z correlation was developed for thermal margin analysis of fuel with the Mark-BW17 grid design. This fuel is 17x17 and has a zircaloy grid with mixing vanes. The BWU-Z correlation has been approved for licensing analysis for this fuel design over the parameter ranges as follows: pressure range 400 to 2465 psia, mass velocity between 0.36 and 3.55 Mlbm/hr-ft^2, equilibrium quality at CHF up to 0.74, design limit minimum departure from nucleate boiling ratio (MDNBR) of 1.19 for pressures greater than 1000 psia, 1.20 for pressure between 700 psia and 1000 psia, and 1.59 for pressure between 400 psia and 700 psia. This review will verify that the use of the BWU-Z CHF correlation with the Mark-B11 spacer grid design is still within the applicable valid ranges of the approved BWU CHF correlations.

The Mark-B11 spacer grid design is a version of the Mark-BW17 grid design that has been modified for use with 15x15 fuel. This spacer grid has the same grid design as the Mark-BW17, but is scaled for a 15x15 rod array. An experimental program was conducted at the Columbia University Heat Transfer Research Facility using electrically heated 5x5 test sections modeling 15x15 fuel with the Mark-B11 grid design.

Information provided in Appendix E of the subject submittal (Reference 1) and in response to the staff's RAIs (References 3 and 4) shows that BWU-Z correlation with the multiplicative factor F_{B11} = 0.98 fits the data set for Mark-B11 grid design quite well. Over the range tested, there is no significant bias with the main independent variables of system pressure, mass velocity, or local equilibrium quality at CHF. The multiplicative factor F_{B11} corrects a non-conservative bias of about 2 percent that is essentially uniform over the full range of the data set.

A total of 216 data points were obtained in five test sections, representing three different subchannel geometries. The 5x5 test section geometries included unit cell (all rods heated), guide tube (central rod simulated an unheated guide tube thimble), and cold cell (all rods except for a cold central rod) configurations. The range of conditions tested is: pressure between 600 and 2465 psia, mass velocity between 0.36 and 3.55 Mlbm/hr-ft^2, and equilibrium quality at CHF up to 0.55.

This data set does not quite span the full range of intended application for the correlation as stated in Reference 2. It does not include any data at pressure down to 400 psia, or equilibrium quality as high as 0.74 at the point of critical heat flux. It does, however, span the full range of application for mass velocity, which means that the missing "corner" of the data space consists of conditions at very low pressure (less than 600 psia). The design limit MDNBR for BWU-Z correlation with Mark-BW17 grid (Reference 2) is specified as 1.20 for pressure between 700 and 1000 psia, and 1.59 for pressure between 400 psia and 700 psia. It is a function of pressure because of the sparse data at low pressure.

Based on our review of the submittal and the responses to the staff's RAI in relation to the approved basis for BWU-Z correlation, the staff has found that the BWU-Z correlation with multiplicative factor F_{B11} = 0.98 is acceptable to Mark-B11 fuel over the range of parameters as follows: pressure between 400 and 2465 psia, mass velocity between 0.36 and 3.55 Mlbm/hr-ft^2, and equilibrium quality at CHF up to 0.74, with a design limit MDNBR of 1.183 for pressure above 1000 psia, 1.20 for pressure between 700 and 1000 psia, and 1.59 for pressure between 400 and 1000 psia.

3.0 CONCLUSION

Based on our review of Addendum 1 to BAW-10199P, the staff has found the application of the BWU-Z correlation, with multiplicative factor F_{B11} = 0.98, to 15x15 fuel with Mark-B11 grids to be acceptable over the range of parameters as follows: pressure between 400 and 2465 psia, mass velocity between 0.36 and 3.55 Mlbm/hr-ft^2, and equilibrium quality at CHF up to 0.74, with a design limit MDNBR of 1.183 for pressure above 1000 psia, 1.20 for pressure between 700 and 1000 psia, and 1.59 for pressure between 400 and 1000 psia.

4.0 REFERENCES

1. FCF Letter (JHT/96-64) from J. H. Taylor to USNRC transmitting Topical Report, BAW-10199P, Addendum 1, "The BWU Critical Heat Flux Correlations, September 1996," September 30, 1996.

2. BAW-10199-P-A, "The BWU Critical Heat Flux Correlations," August 1996.

3. FCF Letter (GR158.doc) from T. A. Coleman to USNRC, "Response to the December 10, 1997, NRC Request for Additional Information," February 23, 1998.

4. FCF Letter (GR810.doc) from T. A. Coleman to USNRC, "Response to the July 27, 1998, NRC Request for Additional Information," October 21, 1998.

5. FCF Letter (GR99-241.doc) from T. A. Coleman to USNRC, "Topical Report BAW-10199P, Addendum 1, The BWU Critical Heat Flux Correlations, TAC:M96728," December 16, 1999.

Attachment: Technical Evaluation Report

Principal Contributor: T. Huang

Date: April 6, 2000

Attachment

TECHNICAL EVALUATION REPORT for

BAW-10199P-A, The BWU Critical Heat Flux Equations, Addendum 1:

Appendix E -- Application of the BWU-Z CHF Correlation to the Mark B11 Spacer Grid Design

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

Judith M. Cuta

May 17, 1999

Prepared for

Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
under Contract DE-ACO6-76RLO 1830
NRC J2435
Pacific Northwest National Laboratory
Richland, WA 99352

SUMMARY

Addendum 1 to BAW10199P, seeks to extend the BWU-Z critical heat flux correlation to fuel with the Mark B11 and Mark BW17 MSM grid designs. After careful review of Appendix E and Appendix F (which comprise Addendum 1), and consideration of the responses to Requests for Additional Information (RAIs), it is recommended that the BWU-Z critical heat flux correlation should be approved for Mark B11 fuel over the full range of application of the BWU-Z correlation. Approval is not recommended for application to fuel with the Mark BW17 MSM grid design, except within the restricted range covered by the data set used to evaluate the correlation's applicability to this design; i.e., pressures in the range 1000 - 2465 psia, mass velocities in the range 1.0 to 3.5 Mlbm/hr-ft^2, qualities below 30 percent at the location of MDNBR, and unit cell subchannel geometry.

BACKGROUND

The BWU-Z CHF correlation was developed for thermal margin analysis of fuel with the BW17 grid design, which is a zircaloy grid with mixing vanes for 17x17 fuel. The correlation has been approved (see Ref. 1) for licensing analysis of this fuel over the range shown in Table 1.

Table 1. Approved Range of Application for BWU-Z CHF Correlation with BW17 Grids

pressure	400 - 2465 psia
mass velocity	0.36 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.74
design limit MDNBR	1.19 for P > 1000 psia 1.20 for 700 psia < P < 1000 psia 1.59 for 400 psia < P < 700 psia

The Mark B11 spacer grid design is a version of the BW17 grid design for use with 15x15 fuel. This spacer grid has the same grid design as the BW17 grid, but is scaled for a 15x15 rod array. An experimental program was conducted at the Columbia University Heat Transfer Research Facility (HTRF) using electrically heated 5x5 test sections modeling 15x15 fuel with the Mark B11 grid design. A total of 216 data points were obtained in five test sections, representing three different subchannel geometries.

The BWU-Z correlation developed for the BW17 grid design was applied to the data obtained in the test bundles modeling the B11 grid design, and was found to fit the B11 data with a 2 percent nonconservative bias. That is, the approved form of the BWU-Z correlation predicts critical heat flux values that are in general approximately 2 percent higher than the measured values obtained in the test assemblies modeling fuel with the B11 grid design. A multiplicative correction factor, F_{B11} = 0.98, was applied to the BWU-Z correlation to correct the fit to the data set. Using this data set, the design limit MDNBR developed for the BWU-Z correlation with the multiplicative correction factor F_{B11} = 0.98 is 1.183.

One test section of the CHF test series conducted in geometries modeling the BW17 grid design included three "mid-span mixing" (MSM) grids inserted in the bundle midway between the BW17 grids in the upper half of the assembly (spans 4, 5, and 6, of the seven spans in the bundle). The Mid-Span Mixing grid is identical to the BW17 grid, except that it is only 0.7" high, and does not provide structural support. Two data sets, identified as BW 18.0 and BW 18.1, were obtained in this test assembly, for a total of 76 data points. The geometry of the test

section was 'unit cell' type; that is, a 5x5 matrix of fuel pin simulators 0.374 inches in diameter on a pitch of 0.422." The model geometry did not include a guide tube, cold rods, or assembly intersection configurations. The data sets obtained in tests BW 18.0 and BW 18.1 were not used in the derivation of the coefficients of the BWU-Z CHF correlation for application to fuel with BW17 grids.

When the approved form of the BWU-Z correlation for fuel with BW17 grids is applied to the MSM data set (i.e., the data from BW 18.0 and BW 18.1), the correlation shows an overall conservative bias of about 15 percent. That is, it predicts critical heat flux values that are approximately 15 percent lower than the values measured in the tests. A multiplicative factor, F_{MSM} = 1.15, was applied to the BWU-Z correlation to correct the fit to this MSM data set. Using this data set, the design limit DNBR developed for the BWU-Z correlation with the multiplicative correction factor F_{MSM} = 1.15 is 1.184.

Application of the BWU-Z correlation to fuel with B11 and MSM grid designs has been documented in Appendix E and Appendix F, respectively, to BAW-10199-P(A) and submitted as Addendum 1. The same range of applicability is asserted for both, as given in Table 1 above. This is the same range as that approved for the BWU-Z correlation for fuel with BW17 grids, as documented in BAW-10199P(A).

EVALUATIONS

Evaluation of the proposed application of the BWU-Z correlation as documented in Appendix E and Appendix F is relatively straightforward, since the correlation has not been reoptimized to fit the data sets for the B11 and MSM grids. It is necessary only to examine the goodness of fit of the correlation to the specific data set, and the completeness of the data set's coverage of the intended range of application. The following subsections cover these points for each of the proposed applications under review.

Evaluation for Appendix E (Mark B11 grid design):

Information presented in Appendix E and in response to Requests for Additional Information (RIAs) shows that the BWU-Z correlation with the multiplicative factor F_{B11} = 0.98 fits the data set for the B11 grid design quite well. Over the range tested, there is no significant bias with the main independent variables of system pressure, mass velocity, or local equilibrium quality at CHF. The multiplicative factor F_{B11} corrects a non-conservative bias of about 2 percent that is essentially uniform over the range of the data set.

The data set is of only moderate size, consisting of 216 data points obtained in five test sections. The 5x5 test section geometries included unit cell (all rods heated), guide tube (central rod simulating an unheated guide tube thimble), and cold unit cell (all rods heated except for a cold central rod) configurations. The range of conditions tested is summarized in the Table 2.

Table 2. Range of CHF Test Conditions for B11 Grid Design

pressure	600 - 2465 psia
mass velocity	0.36 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.55

This data set does not quite span the full range of intended application for the correlation, as described in Table 1. It does not include any data at pressures down to 400 psia, or equilibrium quality as high as 0.74 at the point of critical heat flux. It does, however, span the full range of application for mass velocity, which means that the missing 'corner' of the data space consists of conditions at very low pressure (<600 psia). The design limit for the BWU-Z correlation with BW17 grids is specified as 1.20 for the pressure range 700-1000 psia, and is 1.59 for pressures below 700 psia (refer to the TER for BAW-10199P(A); Ref. 1).

The reasoning used to impose the low pressure range design limits of 1.20 and 1.59 on the BWU-Z correlation for BW17 grids (as presented in Ref. 1) can also be applied to the BWU-Z correlation for B11 fuel. Therefore, the design limit DNBR of 1.183 computed for the BWU-Z correlation for the B11 grid design is applicable to pressures above 1000 psia, while the limit of 1.20 applies in the pressure range 700-1000 psia, and 1.59 in the pressure range 700-400 psia.

Evaluation for Appendix F (Mark BW17/MSM grid design):

Information presented in Appendix F and in response to Requests for Additional Information (RIAs) shows that the BWU-Z correlation with the multiplicative factor F_{MSM} = 1.15 fits the limited data set for the MSM grid design quite well. There is no significant bias with the main independent variables of system pressure, mass velocity, or local equilibrium quality at CHF. There is, however, a definite conservative bias of about 15 percent in the predicted critical heat flux values obtained with the BWU-Z correlation for BW17 grids in its approved form. The multiplicative factor F_{MSM} = 1.15 corrects this bias over the range of the limited data set.

The data set for the MSM grid design is extraordinarily small, consisting of only 76 data points obtained in two test sections. The two test sections both consist of unit cell (all rods heated) geometry, and the data set does not include guide tube or cold unit cell configurations. The range of conditions covered in this small data set is quite limited, as shown in Table 3.

Table 3. Range of CHF Test Conditions for MSM Grid Design

pressure	1000 - 2465 psia
mass velocity	1.0 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.30

The range on pressure is even more limited than the table implies, since there are only three data points at 1000 psia. The rest of the data is at 1500 psia or above. The limited range means that the data set does not provide information on the CHF performance of the MSM grid design at low pressure, low flow rate, and high quality. It is in these regions that otherwise benign grid designs can have unforseen (and often detrimental) effects on mixing and on CHF. The lack of data in the high quality region is of particular concern. The data set extends only up to 30 percent quality, and the proposed range of application of this correlation is up to 74 percent quality. It is highly unlikely that the range of conditions tested included all of the two-phase flow and heat transfer regimes that a fuel bundle with MSM grids might experience under normal operating conditions and operational transients.

Two-phase mixing behavior in rod bundles with mixing vane grids (or without mixing vane grids, for that matter) is poorly understood, and not well characterized by even the most sophisticated multi phase flow modeling tools currently available. Experimental data is required to evaluate heat transfer performance over the full range of conditions expected in the actual fuel bundle. The assumption that the trends observed in the BW 18.0 and BW 18.1 test sections at mass velocities above 1.0 Mlbm/hr-ft^2 will continue unchanged below 1.0 Mlbm/hr-ft^2, even at the higher pressures, is not well-founded and has no supporting data to justify it. This is precisely the region in which sudden shifts in the mechanism of departure from nucleate boiling have been observed in other fuel designs, usually as a result of non-linear phase transitions in boiling flow.

The fit of the approved form of the BWU-Z correlation to this limited data set shows a bias of approximately 15 percent. Although this bias is conservative and essentially uniform over the range of the limited data set, it nevertheless shows that the correlation does not fully capture the critical heat flux behavior in geometries that include MSM grids in addition to BW17 grids. In addition to the simple problem of determining the accuracy of the correlation's predictions in regions where there are no data points, extrapolation to conditions outside the range tested is not justifiable, and there is no means of characterizing the uncertainty of the correlation's predictions in such regions.

The data set is too small and too limited in range to assure that the statistical analysis can properly capture the fit of the correlation to the data base over the full range of intended application, particularly at the lower flow rates and pressures, and higher qualities. Typically, these are the regions where the greatest variability tends to occur. Leaving them out of the calculation entirely makes it very likely that the standard deviation calculated for the fit of the correlation to the 76 data points significantly understates the variance, and results in a lower overall DNBR limit than the correlation really should have. It is not possible to determine if the calculated value of 1.184 for the design limit DNBR provides the required thermal margin protection in regions outside the range of the limited data set. This includes the effect of geometries other than the unit cell at nominal and off-nominal operating conditions. The data set provides no information on how accurately the BWU-Z correlation will predict critical heat flux in subchannels near guide tube thimbles or other cold rod configurations with MSM grids in place.

Given the limitations of the data set and the large bias seen in the BWU-Z correlation when applied to this data, the BWU-Z correlation with the multiplicative F_{MSM} factor can be approved only over the limited range given in Table 4.

Table 4. Range of Applicability of BWU-Z CHF Correlation (with F_{MSM}) for Fuel with MSM Grids

pressure	1000 - 2465 psia
mass velocity	1.0 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.30
subchannel geometry	unit cell only

Within the range of application defined in Table 4, the design limit DNBR for the BWU-Z correlation (with F_{MSM}) for application to fuel with MSM grids is 1.184. The correlation cannot be approved for application over the range defined in Table 1, on the basis of the small limited data set obtained in test sections with MSM grids.

RECOMMENDATIONS

- The BWU-Z correlation with multiplicative factor F_{B11} is applicable to 15x15 fuel with B11 grids over the range of operating conditions shown in Table 5, with design limit MDNBR values as noted for the given pressure ranges.
- The BWU-Z correlation with multiplicative factor F_{MSM} has not been shown to be applicable over the same operating range as that previously approved for the BWU-Z correlation for fuel with BW17 grids. The applicable parameter ranges and design limit MDNBR for this correlation, based on its extremely limited data set, are given in Table 6.

Table 5. Approved MDNBR Limits and Range of Application for BWU-Z CHF Correlation (with F_{B11}) for Fuel with B11 Grids

pressure	400 - 2465 psia
mass velocity	0.36 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.74
design limit MDNBR	1.183 for P > 1000 psia 1.20 for 700 psia < P < 1000 psia 1.59 for 400 psia < P < 700 psia

Table 6. Approved MDNBR Limits and Range of Application for BWU-Z CHF Correlation (with F_{MSM}) for Fuel with MSM and BW17 Grids

pressure	1000 - 2465 psia
mass velocity	1.0 - 3.55 Mlbm/hr-ft^2
equilibrium quality at CHF	up to 0.30
subchannel geometry	unit cell only
design limit MDNBR	1.184 for P > 1000 psia

REFERENCE

1. BAW-10199P(A), The BWU Critical Heat Flux Correlations, D. A. Farnsworth and G. A. Meyer, Framatome Cogema Fuels, August 1996.

The BWU Critical Heat Flux Correlations

Table of Contents

Table of Contents (Cont'd.)

List of Tables

Appendix E

Application of the BWU-Z CHF Correlation to the Mark B11 Spacer Grid Design

Introduction

During 1995 and 1996, FCF 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 B11 mixing vane spacer grid design. In all, 5 tests representing 3 different geometrical configurations were conducted. Each of these multi-point tests was conducted on a 5-by-5 matrix of electrically heated fuel rods. The Mark B11 spacer grid design is a 15-by-15 version of FCF's 17-by-17 Mark BW17 design.

In BAW-10199 [E-1], a new CHF correlation form (the BWU correlation, Section 1.4) was developed and a separate version was qualified for use with each of three different grid design types. The version qualified for use with the Mark BW17 design is termed BWU-Z. BWU-Z was qualified for the Mark BW17 grid with a 20.5 inch pitch (Table 4-1 of BAW-10199). In Appendix F below, a multiplier on the BWU-Z correlation is qualified for use with the Mark BW17 MSM (mid-span-mixer) design. It is the purpose of this appendix to quantify (also in the form of a multiplier on BWU-Z) the CHF capability of the Mark B11 mixing vane spacer grid design.

Test Description

All of the Mark B11 mixing vane CHF tests were performed at the Columbia University HTRF (Heat Transfer Research Facility). 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 E-2.

Individual tests of the Mark B11 test program are summarized in Table E-1. Complete modeling information, including shroud dimensions, power peaking information, form loss coefficients and the like are provided in Tables E-2 through E-5. Individual test data points (bundle condition data) are listed in Table E-6

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 [E-3]. 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 method followed is to use the local conditions data from Table E-1 with the BWU-Z correlation to obtain a multiplier (designated F_{B11}) for the Mark B11 mixing vane spacer grid design.

The Design Limit DNBR for the Mark B11 configuration is then shown to be less than or equal to the 1.19 value qualified in Table 4-1 of BAW 10199 [E-1] for the standard Mark BW17 design. Additionally, the final mean M/P CHF ratio (with the Mark B11 multiplier) is shown to be greater than or equal to 1.0. These dual criteria insure conservatism of the application.

The applicable correlation is

$$(Q_{chf})_{B11} = F_{B11} * FLS * Q_{unif} / F$$

with Q_{unif}, FLS and F the original BWU-Z factors from BAW 10199 [E-1] and F_{B11} determined in this analysis.

Analysis Results

The local conditions analysis was performed as explained above to iterate to a F_{B11} value of 0.983. For application, the F_{B11} will be conservatively rounded down to 0.980. The applicable results are documented in Tables E-7 and E-8 and presented graphically in Figures E-1 through E-3. The resulting design limit with the statistics shown in Table E-7 is

n, # of data	216
N, degrees of freedom (n-1)	215
M/P, avg measured to predicted CHF	1.0040
σ(M/P,N)	0.0868
K (215,0.95,0.95), one sided tolerance factor [E-4]	1.830

$$DNBR(L) = 1 / (M/P - K\,\sigma)$$
$$= 1 / [1.0040 - 1.830(.0868)] = 1.183$$

Conclusion

It has been shown above that the CHF performance of the Mark B11 mixing vane spacer grid design can be described with a simple modification to the BWU-Z correlation.

$$(Q_{chf})_{B11} = F_{B11} * FLS * Q_{unif} / F$$

where F_{B11} = [c,d,e]. FLS, Q_{unif} and F are as defined for BWU-Z in Table 3-1 of BAW 10199 [E-1], with a grid spacing of 21.1 inches, and ranges of applicability as specified in Table 4-1 (also of BAW 10199).

References

E-1. D. A. Farnsworth and G.A. Meyer, "The BWU Critical Heat Flux Correlations," BAW-10199P-A, Framatome Cogema Fuels, August 1996.

E-2. C. F. Fighetti and D.G. Reddy, "Parametric Study of CHF Data," EPRI-NP-2609, 1982 (Volume 1 of 3).

E-3. J. H. Jones, K.J. Firth, J.R. Gloudemans and J.M. Alcorn, "LYNXT Core Transient Thermal-Hydraulic Program," BAW-10156-A, Rev. 1, B&W Fuel Company, August, 1993.

E-4. D. B. Owens, "Factors for One-Sided Tolerance Limits," Sandia Corporation Monograph, 1963.

Table E-1

Mark B11 CHF Test Program Summary

Test	Section	CHF Data
26.0	Unit Cell	32
27.0	Guide Tube [4]	29
27.1	Guide Tube	26
28.0	Unit Cell	63
29.0	Cold Unit	64
30.0	Guide Tube	37

[1] A Unit Cell test consists of a 5-by-5 rod array with all rods heated.

[2] A Guide Tube test consists of a 5-by-5 rod array, all heated except the center rod (#25) which has the guide tube diameter.

[3] A Cold Unit test consists of a 5-by-5 rod array, all heated except the center rod (#25) which has the fuel rod diameter.

[4] Test 27.0 was performed on a non-standard Mark B11 design Thus Tests 27.0 and 27.1 are considered as separate tests. Note that Test 27.0 is not analyzed in this appendix.

Rod Numbering Diagram

1	2	3	4	5
16	17	18	19	6
15	24	25	20	7
14	23	22	21	8
13	12	11	10	9

Table E-2

Mark B11 CHF Test Program
Test Section Geometry Summary

Overall Geometry

[c,d,e]

[1] Form Loss Coefficient
- See Table E-5 for type and location of spacer grids.
- Form loss coefficients for the simple support grids (SS) are 0.25 for all cells but are not used in analysis.

Framatome Cogema Fuels

Table E-3

Mark B11 CHF Test Program
Heater Rod Power Peaking

Test Section/ Description	Hot Rod	Cold Rod
26.0 - Unit Cell		
27.0 - Guide Tube		
27.1 - Guide Tube		
28.0 - Unit Cell		
29.0 - Cold Unit		
30.0 - Guide Tube		

c,d,e

Rod peaking represents actual tested values and is averaged for like rods. Each test section has 16 cold (low power) rods around 9 (unit cell) or 8 (cold unit, guide tube) hot (high power) rods. The cold rods are numbered 1 through 16. The hot rods are numbered 17 through 25. See the diagram on Table E-1.

Note that as per Table E-1 Test Section 27.0 is not included in the analysis for this appendix.

Table E-4

Mark B11 CHF Test Program
Heater Rod Axial Power Distribution

Location, in	$(P/\overline{P})$axial
0.00	0.400
7.17	0.450
14.34	0.547
21.51	0.682
28.68	0.842
35.85	1.014
43.02	1.182
50.19	1.332
57.36	1.449
64.53	1.524
71.70	1.550
78.86	1.524
86.03	1.449
93.20	1.332
100.37	1.182
107.54	1.014
114.71	0.842
121.88	0.682
129.05	0.547
136.22	0.450
143.40	0.400

Table E-5

Mark B11 CHF Test Program
Thermocouple and Spacer Grid Locations

Thermocouple Locations

[c,d,e]

[1] Thermocouples are designated as XX.Y, where XX is the rod number (from 1 to 25) and Y defines the axial location.
[2] Axial location is in inches from the start of the heated length.
[3] B11 = B11 (Vane) mixing grid, SS = simple support grid.

Table E-6

Mark B11 CHF Test Program
Individual Bundle Conditions Data

Columbia ID	Pressure psia	Mass Vel Mlb/hr-ft²	Tin °F	q" Mbtu/hr-ft²	Zchf inches	T/C number
26001						
26002						
26003						
26004						
26005						
26006						
26007						
26008						
26009						
26010						
26011						
26012						
26013						
26014						
26015						
26016						
26017						
26018						
26019						
26020						
26021						
26022						
26023						
26024						
26025						
26026						
26027						
26028						
26029						
26030						
26031						
26032						
27001						
27002						
27003						
27004						
27005						
27006						
27007						
27008						
27009						
27010						
27011						
27012						
27013						
27014						
27015						
27016						
27017						
27018						

c,d,e

Mark B11 CHF Test Program
Individual Bundle Conditions Data

Columbia ID	Pressure psia	Mass Vel Mlb/hr-ft²	Tin °F	q" Mbtu/hr-ft²	Zchf inches	T/C number
27019						
27020						
27021						
27022						
27023						
27024						
27025						
27026						
27027						
27028						
27029						
27101						
27102						
27103						
27104						
27105						
27106						
27107						
27108						
27109						
27110						
27111						
27112						
27113						
27114						
27115						
27116						
27117						
27118						
27119						
27120						
27121						
27122						
27123						
27124						
27125						
27126						
28001						
28002						
28003						
28004						
28005						
28006						
28007						
28008						
28009						
28010						
28011						
28012						
28013						

c,d,e

Table E-6 (Continued)

Mark B11 CHF Test Program
Individual Bundle Conditions Data

Columbia ID	Pressure psia	Mass Vel Mlb/hr-ft²	Tin °F	q" Mbtu/hr-ft²	Zchf inches	T/C number
28014						
28015						
28016						
28017						
28018						
28019						
28020						
28021						
28022						
28023						
28024						
28025						
28026						
28027						
28028						
28029						
28030						
28031						
28032						
28033						
28034						
28035						
28036						
28037						
28038						
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28040						
28041						
28042						
28043						
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28045						
28046						
28047						
28048						
28049						
28050						
28051						
28052						
28053						
28054						
28055						
28056						
28057						
28058						
28059						
28060						
28061						
28062						
28063						

c,d,e

Table E-6 (Continued)

Mark B11 CHF Test Program
Individual Bundle Conditions Data

Columbia ID	Pressure psia	Mass Vel Mlb/hr-ft²	Tin °F	q" Mbtu/hr-ft²	Zchf inches	T/C number
29001						
29002						
29003						
29004						
29005						
29006						
29007						
29008						
29009						
29010						
29011						
29012						
29013						
29014						
29015						
29016						
29017						
29018						
29019						
29020						
29021						
29022						
29023						
29024						
29025						
29026			c,d,e			
29027						
29028						
29029						
29030						
29031						
29032						
29033						
29034						
29035						
29036						
29037						
29038						
29039						
29040						
29041						
29042						
29043						
29044						
29045						
29046						
29047						
29048						
29049						
29050						

Table E-6 (Continued)

Mark B11 CHF Test Program
Individual Bundle Conditions Data

Columbia ID	Pressure psia	Mass Vel Mlb/hr-ft²	Tin °F	q" Mbtu/hr-ft²	Zchf inches	T/C number
29051						
29052						
29053						
29054						
29055						
29056						
29057						
29058						
29059						
29060						
29061						
29062						
29063						
29064						
30001						
30002						
30003						
30004						
30005						
30006						
30007						
30008						
30009						
30010						
30011						
30012						
30013						
30014						
30015						
30016						
30017						
30018						
30019						
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30021						
30022						
30023						
30024						
30025						
30026						
30027						
30028						
30029						
30030						
30031						
30032						
30033						
30034						
30035						
30036						
30037						

c,d,e

Table E-7

M/P CHF RESULTS (Mark B11) with F_{B11}=0.98

Data in this Analysis	216
Mean M/P CHF Ratio	1.0040
Std Dev / Coef Var	0.0868 / 0.0865
Min / Max Values	0.7585 / 1.2323
Des Limit / Normality	1.183 / Accept
Data Out by Range, Outlier	3 / 3
CWF/Fmsm/Grid Ht	1.000/0.980/2.250
Mass Vel Range	0.377 to 3.095
Quality Range	-.0295 to .6025
Pressure Range	595 to 2425
BWU-Z Correlation	Table 3-1

----------Grouped by Test Section----------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
26.0 Unit Cell	32					
27.1 Guide Tube	26					
28.0 Unit Cell	60					
29.0 Cold Unit	61			c,d,e		
30.0 Guide Tube	37					
All Tests	216					

----------Grouped by Mass Velocities, Mlb/hr-ft²----------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
0.5 Mass Vel	15					
1.0 Mass Vel	38					
1.5 Mass Vel	61					
2.0 Mass Vel	47					
2.5 Mass Vel	35			c,d,e		
3.0 Mass Vel	20					
All Mass Vel	216					

----------Grouped by Pressures, psia----------

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
550 to 900	14					
900 to 1250	15					
1250 to 1650	40					
1650 to 1950	44					
1950 to 2250	55					
2250 to 3200	48			c,d,e		
All Pressures	216					

Table E-7 (Continued)

M/P CHF RESULTS (Mark B11) with F_{B11}=0.98

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

GROUP	DATA	AVG	S.D.	MAX	MIN	C.V.
Below 5%	47					
5% to 10%	40					
10% to 15%	62					
15% to 20%	24					
20% to 25%	14			c,d,e		
25% to 30%	8					
Above 30%	21					
All Qualities	216					

-----------Out of Range Data----------

ID	
28061	c,d,e
28062	
28063	

-----------Outliers (by M/P Value)----------

ID	
29051	
29059	c,d,e
29064	

Table E-8

M/P CHF RESULTS (Mark B11) with F_{B11}=0.980

Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
26001							
26002							
26003							
26004							
26005							
26006							
26007							
26008							
26009							
26010							
26011							
26012							
26013							
26014							
26015							
26016							
26017							
26018							
26019							
26020							
26021							
26022							
26023							
26024							
26025							
26026							
26027							
26028							
26029							
26030							
26031							
26032							
27101							
27102							
27103							
27104							
27105							
27106							
27107							
27108							
27109							
27110							
27111							
27112							
27113							
27114							
27115							
27116							
27117							

c,d,e

Table E-8 (Continued)

M/P CHF RESULTS (Mark B11) with F_{B11}=0.980

Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
27118							
27119							
27120							
27121							
27122							
27123							
27124							
27125							
27126							
28001							
28002							
28003							
28004							
28005							
28006							
28007							
28008							
28009							
28010							
28011							
28012							
28013							
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28015							
28016							
28017							
28018							
28019							
28020							
28021							
28022							
28023							
28024							
28025							
28026							
28027							
28028							
28029							
28030							
28031							
28032							
28033							
28034							
28035							
28036							
28037							
28038							
28039							
28040							

c,d,e

Table E-8 (Continued)

M/P CHF RESULTS (Mark B11) with F_{B11}=0.980

Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
28041							
28042							
28043							
28044							
28045							
28046							
28047							
28048							
28049							
28050							
28052							
28052							
28053							
28054							
28055							
28056							
28057							
28058							
28059							
28060							
29001							
29002							
29003							
29004							
29005							
29006							
29007							
29008							
29009							
29010							
29011							
29012							
29013							
29014							
29015							
29016							
29017							
29018							
29019							
29020							
29021							
29022							
29023							
29024							
29025							
29026							
29027							
29028							
29029							

c,d,e

Table E-8 (Continued)

M/P CHF RESULTS (Mark B11) with F_{B11}=0.980

Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
29030							
29031							
29032							
29033							
29034							
29035							
29036							
29037							
29038							
29039							
29040							
29041							
29042							
29043							
29044							
29045							
29046							
29047							
29048							
29049							
29050							
29052							
29053							
29054							
29055							
29056							
29057							
29058							
29060							
29061							
29062							
29063							
30001							
30002							
30003							
30004							
30005							
30006							
30007							
30008							
30009							
30010							
30011							
30012							
30013							
30014							
30015							
30016							
30017							

c,d,e

Table E-8 (Continued)

M/P CHF RESULTS (Mark B11) with F_{B11}=0.980

Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
30018							
30019							
30020							
30021							
30022							
30023							
30024							
30025							
30026			c,d,e				
30027							
30028							
30029							
30030							
30031							
30032							
30033							
30034							
30035							
30036							
30037							

Figure E-1 - Mark B11 Vane Data
Measured to Predicted CHF versus Mass Velocity

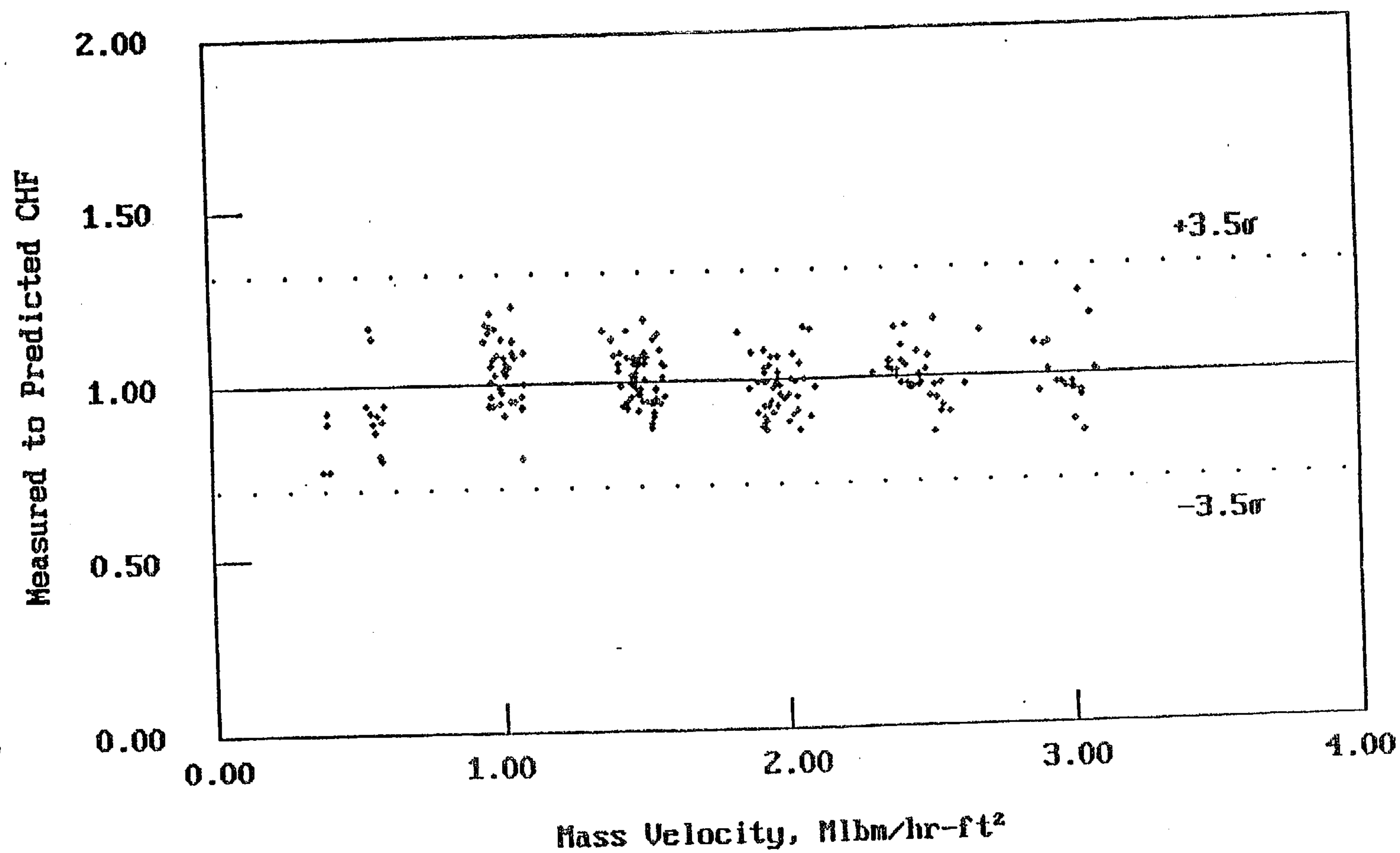


Figure E-2 – Mark B11 Vane Data
Measured to Predicted CHF versus Quality

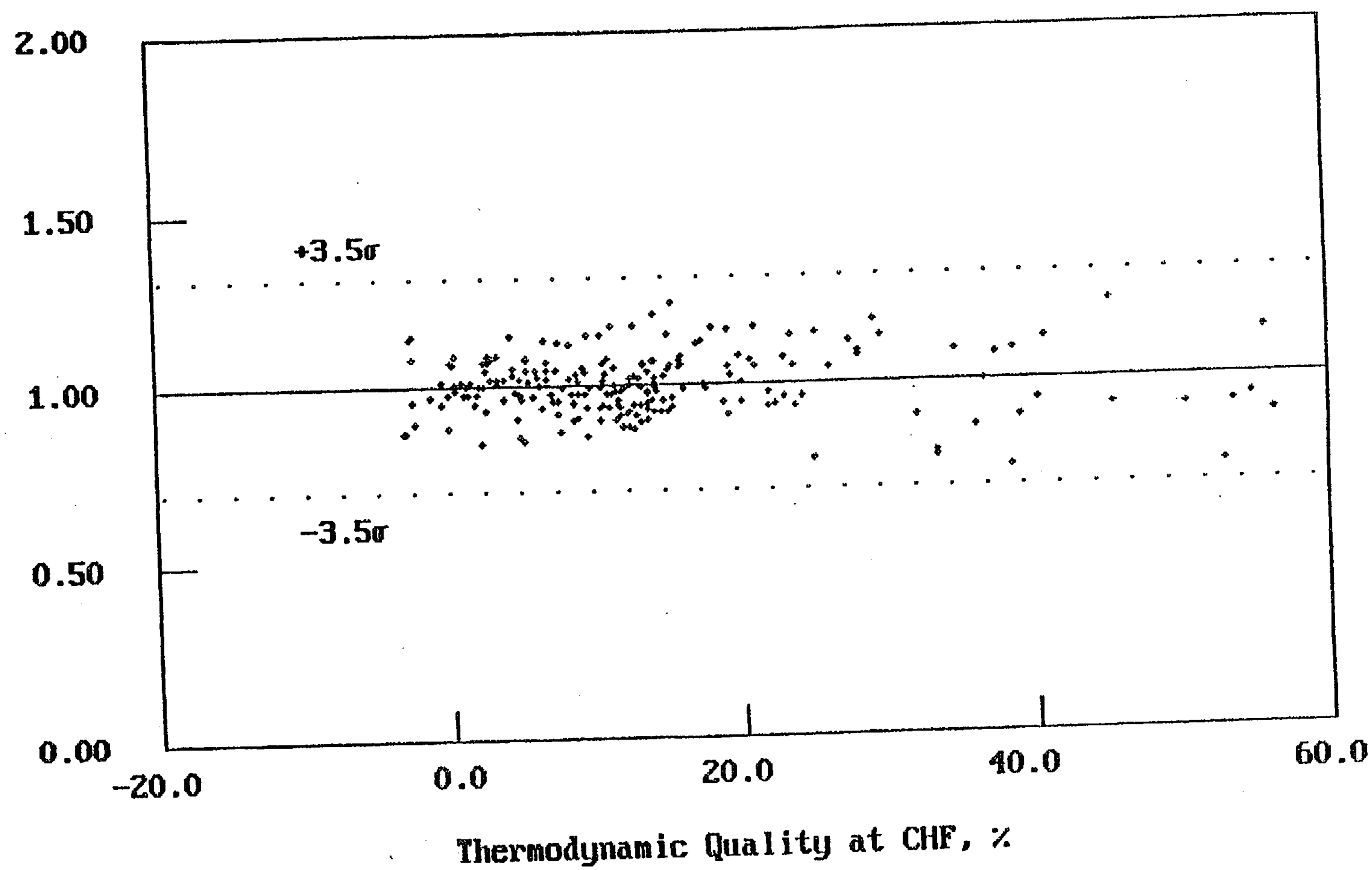
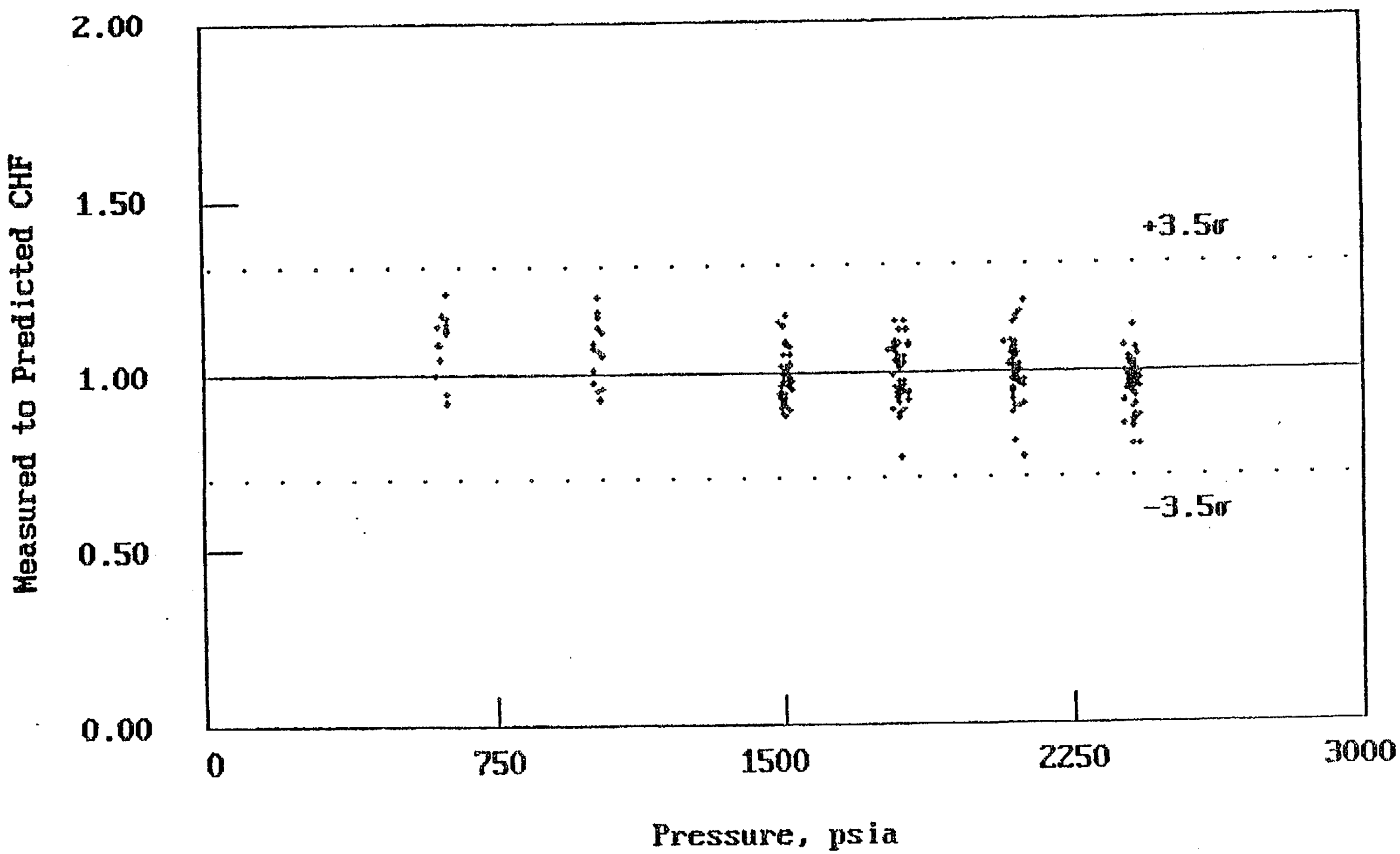


Figure E-3 - Mark B11 Vane Data
Measured to Predicted CHF versus Pressure



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 BW17 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 BW17 design is termed BWU-Z. BWU-Z was qualified for the Mark BW17 grid with a 20.5 inch pitch (Table 4-1). As was shown in Reference F-1, 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 BW17 design with MSM grids.

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 and the like are 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 method followed is to 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 BW17 design spaced at 20.5 inches. Additionally, the final mean M/P CHF ratio (with the MSM multiplier) is shown to be greater than or equal to 1.0. These dual criteria insure conservatism of the application.

The applicable correlation is then

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

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

Analysis Results

The local conditions analysis was performed as explained above to iterate to a F_{MSM} value of [c,d,e]. For application, the F_{MSM} will be [c,d,e]. The applicable results are documented in Tables F-2 and F-3 and presented graphically in Figures F-1 through F-3. The resulting design limit with the statistics shown in Table F-2 is

n, # of data	76
N, degrees of freedom (n-1)	75
M/P, avg measured to predicted CHF	1.0529
σ(M/P,N)	0.1055
K (76,0.95,0.95), one sided tolerance factor [F-6]	1.974

DNBR(L) = 1 / (M/P - K σ)

= 1 / [1.0529 - 1.974(.1055)] = 1.184

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} = 1.15. 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).

[c,d,e]

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. 1, B&W Fuel Company, August, 1993.

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

Table F-1

Mark BW17 CHF Test Summary

Test	Type [1]	Matrix	AFS [2]	Pin OD inch	Pitch inch	G/T OD inch	Heated Length inches	Grid Spacing inches
Mark BW Data (Columbia HTRF)								
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

[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 grid at 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 (MSM Test 18) with F_{MSM}=1.150

Data in this Analysis	76
Mean M/P CHF Ratio	1.0529
Std Dev / Coef Var	0.1055 / 0.1002
Min / Max Values	0.8337 / 1.2733
Des Limit / Normality	1.184 / Accept
Data Out by Range, Outlier	0 / 0
CWF/Fmsm/Grid Ht	1.000/1.150/2.250
Mass Vel Range	0.909 to 3.385
Quality Range	0.0205 to .4872
Pressure Range	1005 to 2425
BWU-Z Correlation	Table 3-1

c,d,e

Table F-3

M/P CHF RESULTS (MSM Test 18) with F_{HSM}=1.150
Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
18001							
18002							
18103							
18004							
18005							
18006							
18007							
18008							
18009							
18010							
18011							
18012							
18013							
18014							
18015							
18016							
18017							
18018							
18119							
18120							
18121							
18122							
18123							
18124							
18125							
18126							
18127							
18128							
18129							
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18136							
18137							
18138							
18139							
18140							
18141							
18142							
18143							
18144							
18145							
18146							
18147							
18148							
18149							
18150							
18151							
18152							

c,d,e

Table F-3 (Continued)

M/P CHF RESULTS (MSM Test 18) with F_{HSM}=1.150
Individual Results

ID	M/P CHF	Meas CHF btu/hr-ft²	Press psia	Mass Vel lb/hr-ft²	Quality @ CHF	Z chf inches	F Fact
18153							
18154							
18155							
18156							
18157							
18158							
18159							
18160							
18161							
18162							
18163				c,d,e			
18164							
18165							
18166							
18167							
18168							
18169							
18170							
18171							
18172							
18173							
18174							
18175							
18176							

Figure F-1 - Mid-Span-Mixer Data
Measured to Predicted CHF versus Mass Velocity

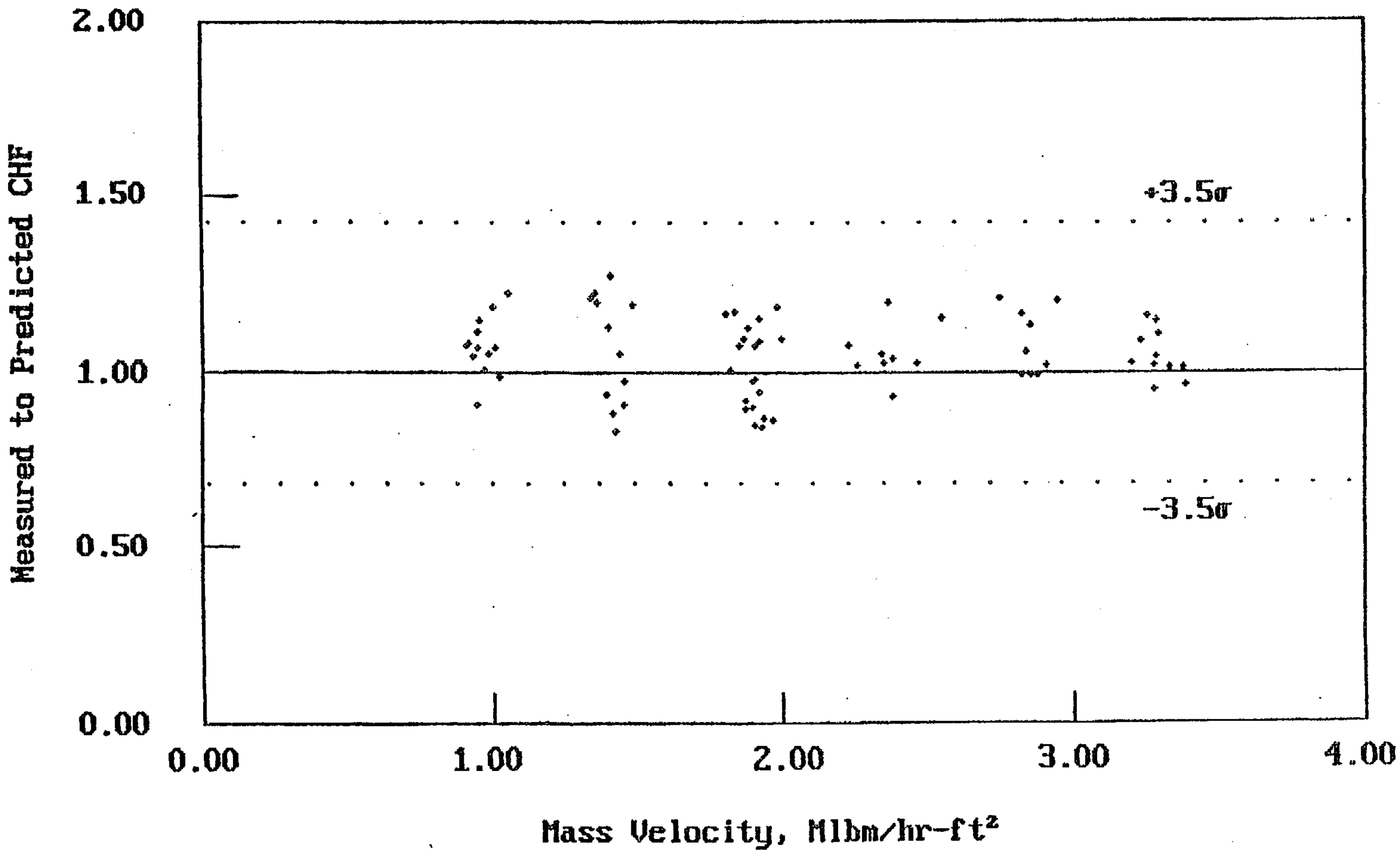


Figure F-2 - Mid-Span-Mixer Data
Measured to Predicted CHF versus Quality

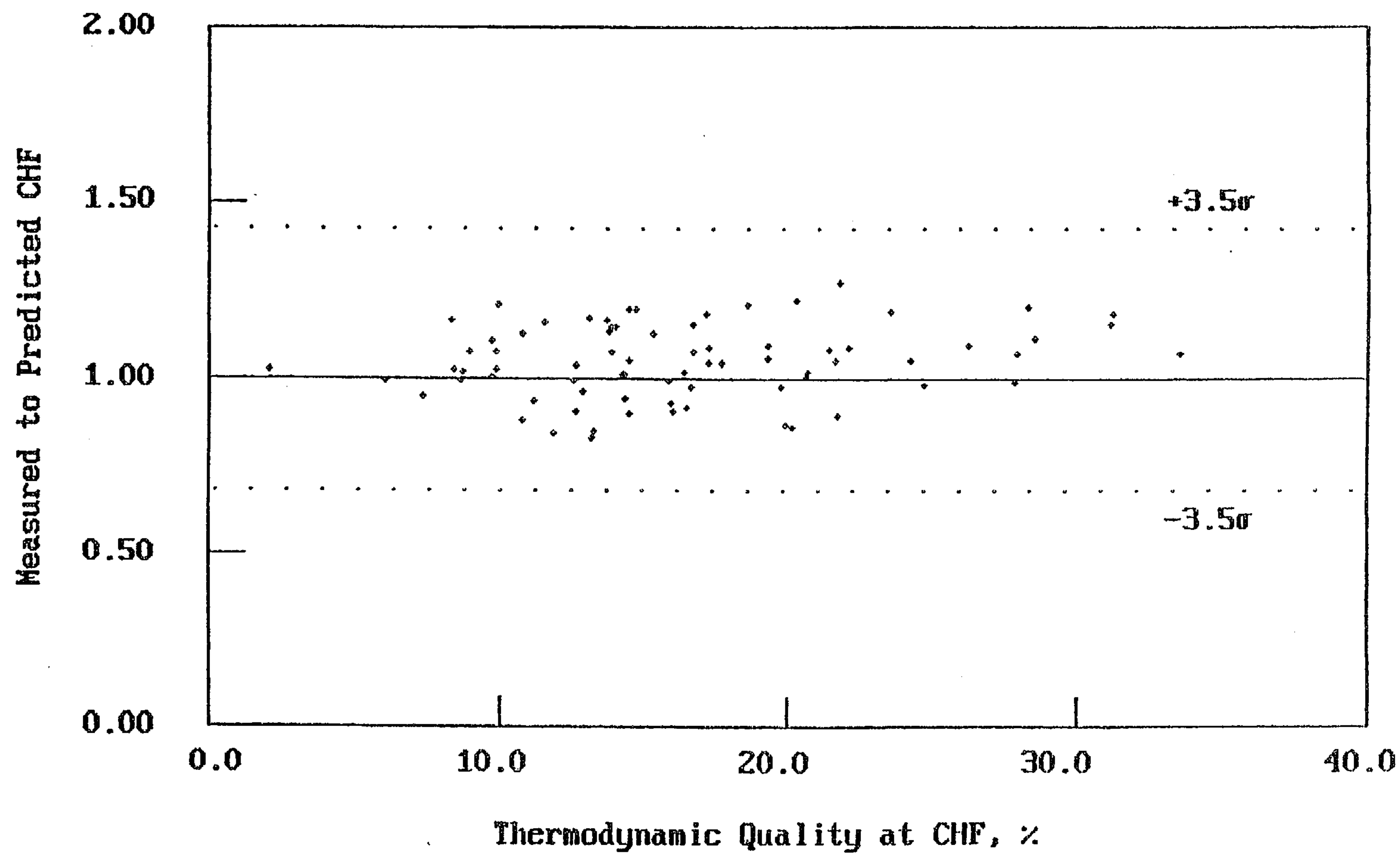
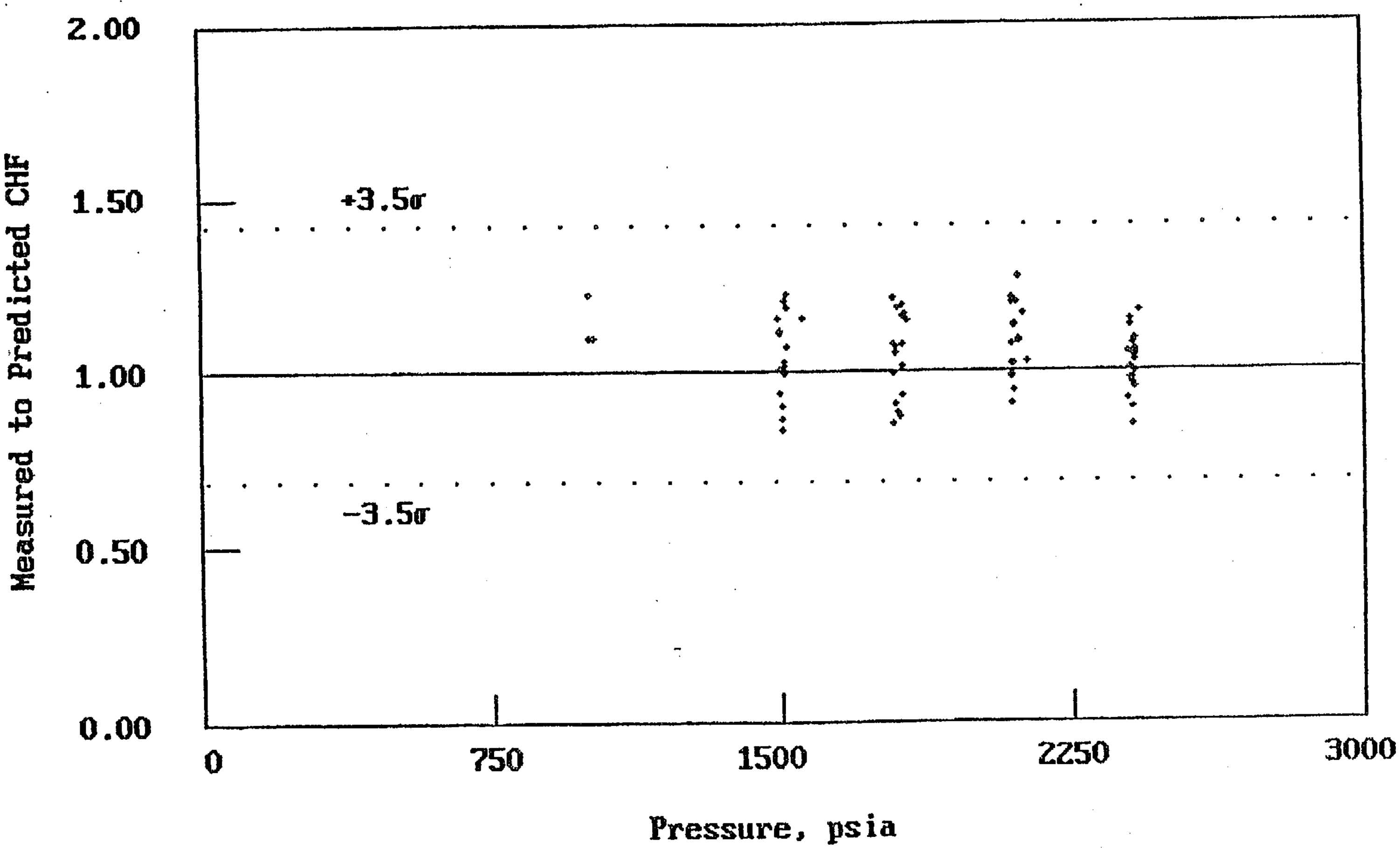


Figure F-3 - Mid-Span-Mixer Data
Measured to Predicted CHF versus Pressure



Appendix G

Documented Response to RAI-1 Dated February 23, 1998

Request for Additional Information for Addendum 1 to BAW-10199P-A

QUESTION 1

Describe schematically the spacer grid designs for Mark B11, Mark BW17 MSM (mid-span-mixer), and Mark BW17 and identify their differences in the bundle geometrical configurations and the thermal-hydraulic performance with respect to that of the Mark BW17 design.

RESPONSE 1

The Mark BW17 spacer grid is comprised of a square array of zircaloy strips used to maintain the correct cross sectional geometry for the fuel rod array of the Mark BW17 fuel assembly. The 0.374 inch diameter fuel rods are arranged in the 17-by-17 array with a pitch of 0.496 inches. At the intersection of each strip, there are two mixing vanes bent at an angle nominally { }[c,e] degrees from the vertical and encircling about one quarter of each adjacent fuel rod. The purpose of these mixing vanes is to enhance the thermal-hydraulic performance of the Mark BW17 fuel assembly by intermixing coolant from adjacent channels, increasing the general turbulence level, and precluding or delaying the formation of a steam film on the surface of the fuel rod. Mark BW17 spacer grids are 2.25 inches in height and are spaced axially along the fuel assembly at 20.5 inch intervals. Based on Reference 1, the BWU-Z CHF correlation was approved to describe the thermal-hydraulic (CHF) performance of the Mark BW17 spacer grid.

The vane size, shape and pattern of the Mark BW17 MSM (mid-span-mixer grid, test BW 18 in Table F-1) is identical to that of the Mark BW17 structural spacer (tests BW 12-17, 19 and 20 in Table F-1). The MSM grid, however, is only { }[e] inches in height. Its purpose is solely for enhancement of the Mark BW17 CHF performance and it is not used for structural strength or geometry control (as the structural spacer grid is). MSM grids are placed midway between the top four zircaloy structural grids in the upper spans of the Mark BW17 MSM fuel assembly.

The Mark B11 spacer grid is a geometrically scaled version of the Mark BW17 spacer grid. The main difference is that it is used to support 0.416 inch diameter fuel rods in a 15-by-15 array with a 0.568 inch pitch. The vane shape and pattern of the Mark B11 spacer grid mixing vanes are identical to those of the Mark BW17 spacer grid. The vanes are proportionally larger. The grid heights of

the Mark B11 and Mark BW17 are the same. The similarity of these grid designs is shown in the photographs of Figures Q-1.1 and Q-1.2.

The most important factor in the determination of the thermal hydraulic performance of a mixing vane spacer grid is the mixing vane. The following table is a detailed comparison of the Mark BW17, the Mark BW17 MSM and the Mark B11 vane designs. The dimensions are in inches and are referenced to Figure Q-1.3. Note that the ratio for dimensions A through D of { }[c,d,e] is the ratio of the Mark B11 pitch (0.568") to that of the Mark BW17 (0.496"). Dimensions E through I describe the weld nugget cutout and weld tab and thus are the same for each design (with a ratio of { }[c,d,e]). Finally, the ratio for the dimension J radius is slightly lower than the pitch ratios to preserve the vane to rod clearance.

Dimension	MK BW17/MK BW17 MSM	MK B11	Ratio
A	{		}[c,d,e]
B	{		}
C	{		}
D	{		}
E	{		}
F	{		}
G	{		}
H	{		}
I	{		}
J	{		}

In summary, from a thermal-hydraulic (CHF) enhancement standpoint, all three grids are conceptually and functionally identical. The levels of thermal-hydraulic performance are virtually identical as detailed in the addendum and in the response to question 3. The multiplier for the Mark B11 { }[c,d,e] is within accepted CHF uncertainty. The multiplier for the Mark BW17 MSM { }[c,d,e] is a conservative enhancement based on the configuration (mid-span placement).

QUESTION 2

Describe the data bases obtained from 5 tests in 3 different geometrical configurations on a 5-by-5 matrix of electrically heated fuel rods, and explain why the tests are applicable to a 15-by-15 and a 17-by-17 Mark BW17 design and the obtained data are sufficient to support new critical heat flux correlation for the Mark B11.

RESPONSE 2

The data base for the Mark B11 design consists of 216 data from five separate tests on three different geometries. These different geometries are described in detail in Tables E-1 and E-2. The tests used to qualify the original Mark BW17 design (530 data, 10 tests and 4 geometries) are detailed in Reference 5.

Data from 5-by-5 (or 4-by-4) tests such as these are universally used to determine the CHF performance of full sized grids (i.e., 15-by-15 or 17-by-17 arrays). The 5-by-5 matrix provides 36 subchannels (or cells). The CHF observations are virtually always in the center four cells surrounding the center rod. The different geometries model the different subchannel configurations in the following ways:

A Unit Cell test (tests 26 and 28) determines the performance of the typical cell in a fuel assembly. This cell is composed of four active fuel rods in each corner and is represented in the CHF test by the central four cells surrounding the center rod (rod 25 in the diagram in Table E-1).

A Guide Tube test (tests 27 and 30) determines the performance of the thimble cell in a fuel assembly. This cell is composed of three active fuel rods with an unheated control rod guide tube in the fourth corner and is represented in the CHF test by the central four cells surrounding the unheated center rod (again rod 25 but unheated and with the guide tube diameter).

A Cold Unit test (test 29) determines the performance of a cell in a fuel assembly containing an unheated fuel rod. This cell is composed of three active fuel rods with an unheated fuel rod in the fourth corner. An unheated fuel rod is sometimes inserted into a fuel assembly found to have a damaged fuel rod. It is represented in the CHF test by the four cells surrounding the unheated center rod (again rod 25 but unheated and with the fuel rod diameter).

The Mark B11 grid design is virtually identical to that of the Mark BW17 except for geometric scaling (see the answer to question 1, above). In addition, the BWU-Z CHF correlation was found to describe the thermal-hydraulic performance of the Mark B11 design with the addition of a simple multiplier (see the answer to question 3, below). These two observations and the three cell geometries tested assure that the Mark B11 data base is sufficient to allow the BWU-Z correlation to be used to represent the CHF performance of the Mark B11 fuel assembly.

QUESTION 3

The data bases for the BWU-Z correlation do not include test data for the Mark B11 and Mark BW17 MSM design. Explain why the BWU-Z correlation is still valid for the Mark B11 and Mark BW17 MSM. Provide the bases which conclude that a simple multiplier is valid for the proposed applications. Describe how accurate and conservative a proposed simple multiplier to the BWU-Z correlation is derived based on limited Mark B11 and Mark BW17 data bases. Provide the procedures to obtain the simple multiplier and justify that the numbers for F_{B11} and F_{MSM} shown in Tables E-7 and E-8, and Tables F-2 and F-3, respectively, are the best results.

RESPONSE 3

The BWU CHF correlations [1] were developed to describe the thermal-hydraulic behavior of three types of PWR spacer grids. These were the BWU-N correlation for non-mixing vane spacer grids, the BWU-I correlation for the first generation inconel mixing vane spacer grids, and the BWU-Z correlation for the high performance Mark BW17 zircaloy mixing vane spacer grid. The form of each correlation is the same, but the correlation coefficients were optimized to their respective data bases for each grid design.

On the other hand, the Mark BW17 MSM and Mark B11 designs are virtually identical to the design of the Mark BW17. As described in the answer to question 1, the Mark BW17 MSM vanes are identical to those of the original Mark BW17 (the grid is simply shorter), and the Mark B11 vanes are scaled up from those of the Mark BW17 (the grid height is the same). This would imply, then, that the same mixing mechanism would apply between these three grids and that, at most, the average level would change.

This implication was examined in two ways. First the data from the new tests were analyzed with the BWU-Z correlation and examined for independent variable bias. No bias was found, only the average levels were different. Next, the coefficients for the BWU equation were reoptimized for each new data base. These coefficients were examined and found to be quite close to the original BWU-Z coefficients with only fairly constant average level multipliers. These verifications indicated that, with an appropriate global multiplier, the BWU-Z correlation would accurately describe the CHF capability of the new grid types.

The multipliers, {   }, [c,d,e] were determined by iterating to conservatively rounded values which, when combined with the BWU-Z

correlation and analyzed over the appropriate data base, resulted in a design limit DNBR less than or equal to that of the original Mark BW17 data base (1.19). For the Mark B11 data base, the calculated design limit DNBR was { } [c,d,e], and for the Mark BW17 MSM data base it was { }. [c,d,e] A slight amount of conservatism is thus introduced by applying the original design limit of 1.19 to the two new applications.

Further evidence of the appropriateness of the multiplicative approach is shown in the independent variable plots of Figures E-1 to E-3 for the Mark B11 data base and Figures F-1 to F-3 for the Mark BW17 MSM data base. These plots were generated using the original BWU-Z correlation with the appropriate multiplier. There is no evidence of independent variable bias in these plots.

QUESTION 4

Table E-1 states that Test 27.0 and 27.1 are considered as separate tests and notes that Test 27.0 is not analyzed in this appendix E. Explain the purpose of the test for unit cell, guide tube and cold unit, and why Test 27.0 is not analyzed but still listed in the Table E-1.

RESPONSE 4

The three geometries of the Mark B11 data base (unit cell, guide tube and cold unit) are representative of the geometries in a Mark B11 fuel assembly. It is important to test differing geometries when qualifying a new grid design with a CHF correlation to insure that the correlation describes the possible geometries to be encountered. The grids for each of the tests analyzed in Appendix E (26.0, 27.1, 28.0, 29.0, and 30.0) were identical in design (mixing vane size, pattern, angle, etc.). This set of five tests, then, comprise a sufficient data base for the Mark B11 spacer grid design (see also the answer to question 2, above).

Test 27.0 was a developmental test conducted with a modified mixing vane design, and thus could not be used as part of the data base for the final Mark B11 design. The data of test 27.0 would have been included in the Mark B11 data base if the modified vane design had been shown to have no effect on the thermal-hydraulic performance of the Mark B11 design. The test was listed in order to explain why the first guide tube test included in the data base was numbered as 27.1 instead of 27.0.

QUESTION 5

It appears that only one axial power distribution (Table E-4) was used in the Mark B11 CHF tests program. Provide the justification that the data obtained from this single axial power shape will support the proposed methodology for the Mark B11 fuel design by adopting the old BWU-Z correlation without even changing its coefficients.

RESPONSE 5

Current CHF testing is almost always carried out using non-uniform axial heat flux heater rods as opposed to the artificial uniform axial heat flux shape. Virtually all modern critical heat flux correlations utilize the same basic form: a main part to describe the uniform CHF as a function of the main independent variables (local condition thermal-hydraulic variables and fuel assembly geometric variables), and a separate modifier to account for the non-uniform axial heat input.

This non-uniform modifier is usually the well known Tong F-Factor and is mainly a function of the axial flux shape. The original Tong F-Factor was developed from limited non-uniform CHF data in comparison with uniform tubular data [2]. It was later, however, shown to be valid for the entire Westinghouse WRB-1 CHF correlation data base [3]. The WRB-1 data base of over 1100 data included CHF tests having four differing non-uniform axial flux shapes with two different heated lengths.

The BWU-Z correlation F-Factor utilizes the Tong form (with different coefficients) and was first developed by FCF (then Babcock & Wilcox) in Reference 4 (for the BWCMV correlation). The F-Factor form is shown in Reference 1 (page 1-4). Like the Westinghouse factor, it was verified with data from several non-uniform flux shape tests (six shapes with three different heated lengths).

When the BWU-Z correlation was developed from the Mark BW17 data base, only one axial power shape was used. However, the original BWCMV F-Factor was shown to be applicable to this 492 point, 7 test data base [5]. (That is, when the correlation was used with the BWCMV F-Factor, no bias with respect to any of the independent variables was observed.) This is again the case with the 216 point, 5 test Mark B11 data base.

In other words, even though the Mark B11 data base has only one distinct axial flux shape, the F-Factor used to describe this data base is based on and has been verified with six distinct shapes. Thus, the retention of the original BWCMV F-Factor of Reference 4 is justified in that its use with the established BWU-Z correlation introduces no independent variable bias into the Mark B11 data base.

QUESTION 6

Based on the data shown in table E-5, there are six thermocouple locations. However, there are 21 heater rod axial powers in Table E-4. Describe the procedures to generate these data. Also, explain the setup on the spacer grid locations with respect to the application to the tests and data obtained for comparison with the data bases for the BWU-Z correlation and why B15 is at -4.47 inches in Table E-5.

RESPONSE 6

The purpose of the rod thermocouples listed in Table E-5 is to detect the sharp clad temperature rise associated with the transition from nucleate to film boiling (CHF). When this increase is detected, the electrical power to the rods is reduced for a return to the nucleate boiling regime thus preventing rod damage. (CHF test heater rods are resistance heated through the rod wall and could melt if the internally generated heat could not be dissipated.)

The rod thermocouples are generally placed at five critical axial locations on each of the inner nine high power rods in the upper half of the test assembly, specifically about one inch upstream and also midway between the grids. Only the locations one inch upstream of the grids have thermocouples in the outer sixteen low power rods. In current CHF testing, virtually all CHF detections are observed just upstream of the grids - thus the upstream thermocouples. The midspan thermocouples are mainly for detection of abnormal CHF caused by, say, mechanical occurrences such as rod deformation (bowing) or channel blockage. Such mechanical abnormalities could eventually cause severe bundle damage - thus the midspan thermocouples.

The heat flux from the rods in CHF testing is generated in the heater tube wall by resistance heating. The non-uniform axial heat flux is generated by wall thickness variations (and thus electrical resistance variations) axially in the heater tube. The outer diameter of the heater tubes is constant so the inner diameter is variable. The highest axial power is generated where the rod is axially thinnest and vice versa. The rod power distribution in Table E-4 shows the ratio of the local heat flux at an axial location to the average heat flux of that heater rod. The heater rod axial powers (Table 4) are not related to the thermocouples (Table E-5).

The spacer grids are positioned axially at the same relative locations as for a full sized production fuel assembly. This was also true of the spacer grids for

the tests for the BWU-Z data base (based on the Mark BW17 fuel assembly design) [5]. The CHF test assemblies are of the same heated length as the production assemblies, but are in a 5-by-5 array (as opposed to the 15-by-15 array for the Mark B11 design and the 17-by-17 array for the Mark BW17 design). The -4.47 inch axial location of grid B15 indicated that this grid is positioned 4.47 inches before the start of the heated length. This is true for both the CHF test assembly and the production Mark B11 fuel assembly.

QUESTION 7

Provide the experimental data to support the form loss coefficients shown in Table E-2 under cell geometry, and describe the procedures to obtain these data including the approved methodologies used.

RESPONSE 7

Form loss coefficients are determined experimentally for full spacer grids. As described in Reference 6, pressure drop data across spacer grids is used to develop overall grid form loss coefficients. The grid form loss value is { } c,d,e for the Mark B11 mixing vane design.

Individual subchannel form loss coefficients are { }.c,e Coolant flow produces irreversible pressure losses at spacers due to the form drag of the strips, the soft and hard stops, the mixing vanes, and the skin friction (of the strips). In the calculation of the subchannel form loss coefficients, individual drag coefficients are used for each of these obstructions along with the detailed subchannel geometry. The resulting set of simultaneous equations is iteratively solved with an equal pressure drop boundary condition. The resulting individual subchannel form loss coefficients are then adjusted to produce the measured overall grid form loss coefficient.

Calculated CHF values have been shown to be insensitive to the absolute value of the overall grid form loss coefficient [5]. CHF sensitivity is determined by the distribution of the subchannel form losses. As discussed in Reference 6, Laser Doppler Velocimeter testing is used to confirm the distribution of subchannel form loss coefficients. The overall form loss coefficient of the 5-by-5 CHF test grids is { }.c,d,e This value is slightly higher than the value for the full 17-by-17 grid ({ } c,d,e) because only the higher resistance interior subchannels are modeled in the 5-by-5 grids.

References

1. D.A. Farnsworth and G.A. Meyer, "The BWU Critical Heat Flux Equations," BAW-10199P-A, Framatome Cogema Fuels, August, 1996.
2. L.S. Tong, "Boiling Crisis and Critical Heat Flux," TID-25887, AEC Critical Review Series, U.S. Atomic Energy Commission, 1972.
3. F.E. Motley et. al., "New Westinghouse Correlation WRB-1 for predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids," WCAP-8763, Westinghouse Electric Corporation, July, 1976.
4. D.A. Farnsworth and G.A. Meyer, "BWCMV - Correlation of Critical Heat Flux in Mixing Vane Grid Fuel Assemblies," BAW-10159P-A, B&W Fuel Company, July, 1990.
5. D.A. Farnsworth and G.A. Meyer, "CHF Testing and Analysis of the Mark BW Fuel Assembly Design," BAW-10189P-A, Framatome Cogema Fuels, January, 1996.
6. "Mark-B11 Fuel Assembly Design Topical Report," BAW-10229P, Framatome Cogema Fuels, September, 1996.

Figure Q-1.1

Mark BW17 Mixing Vane Spacer Grid

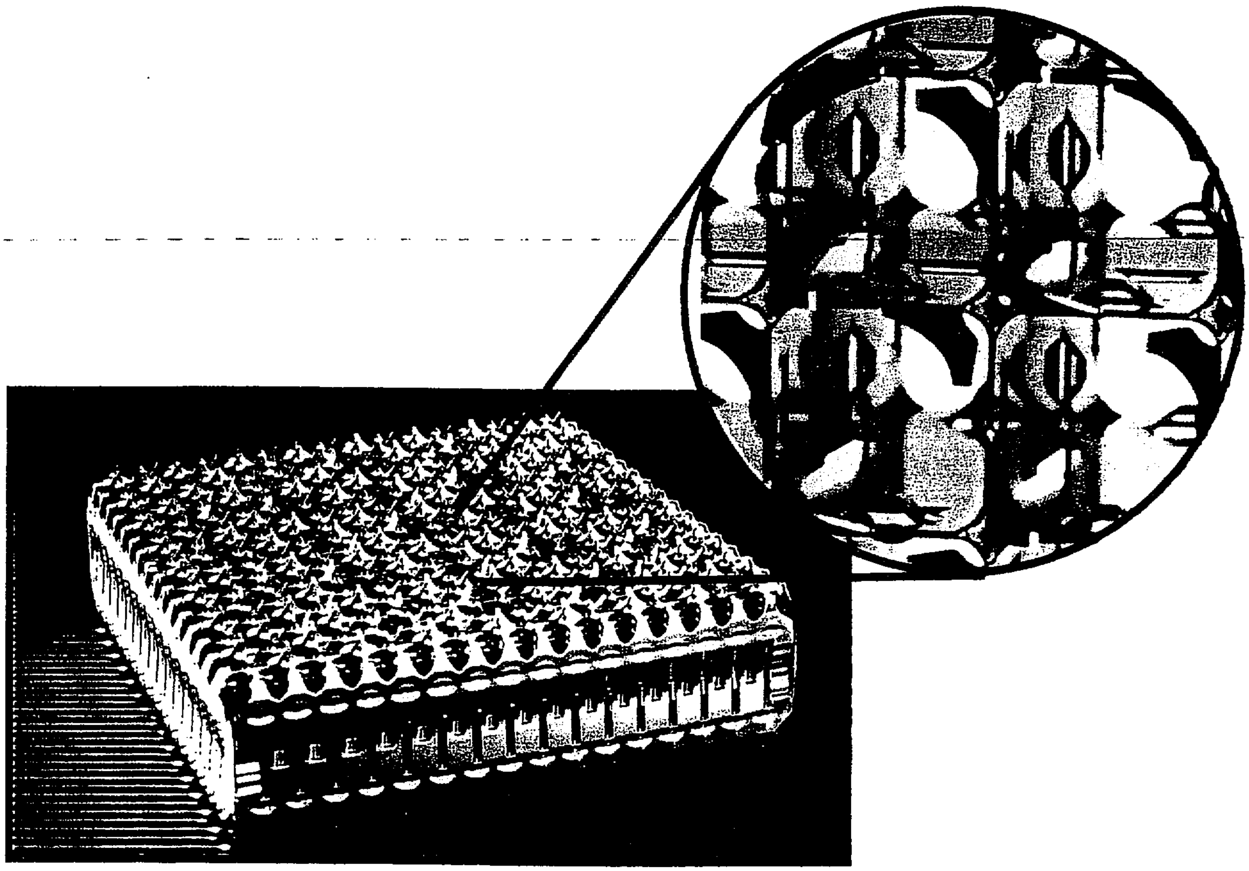


Figure Q-1.2

Mark B11 Mixing Vane Spacer Grid

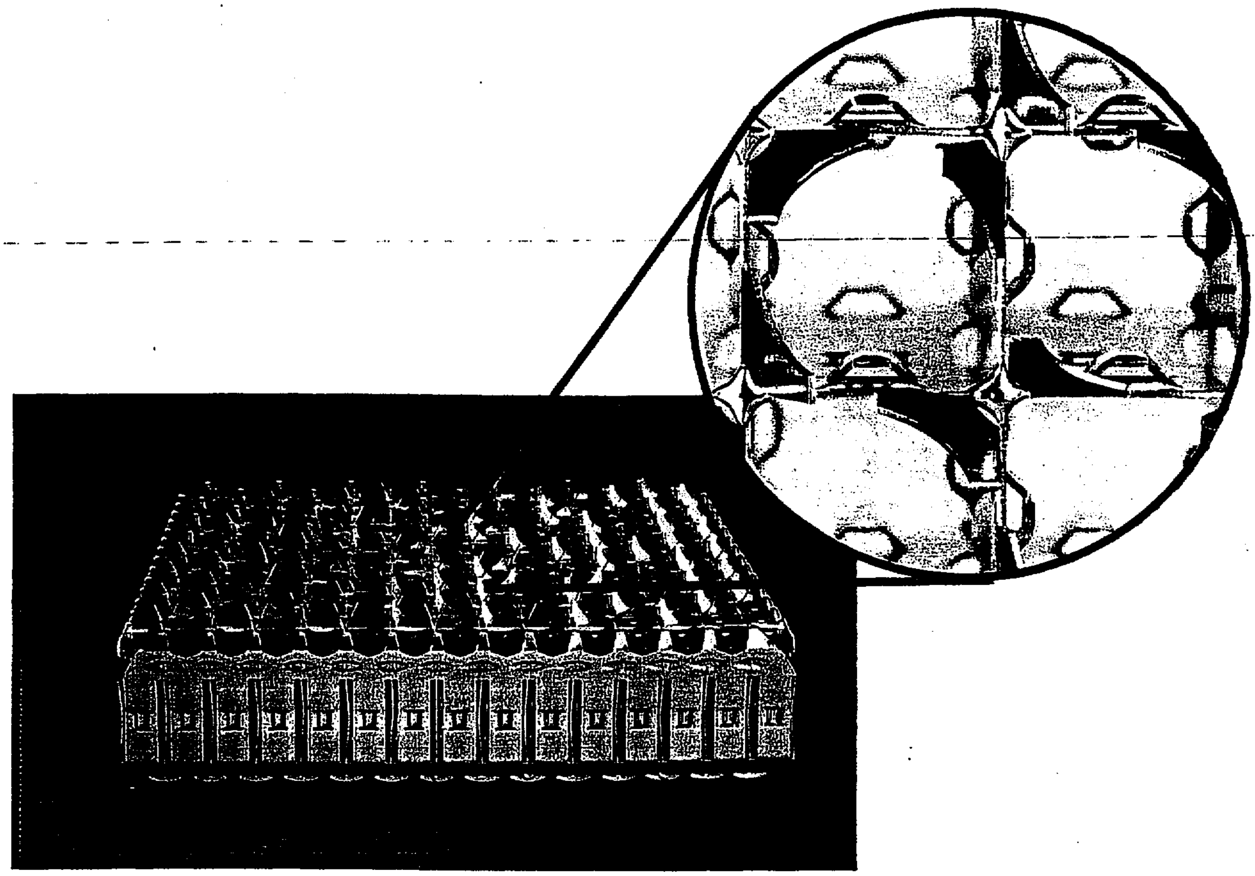
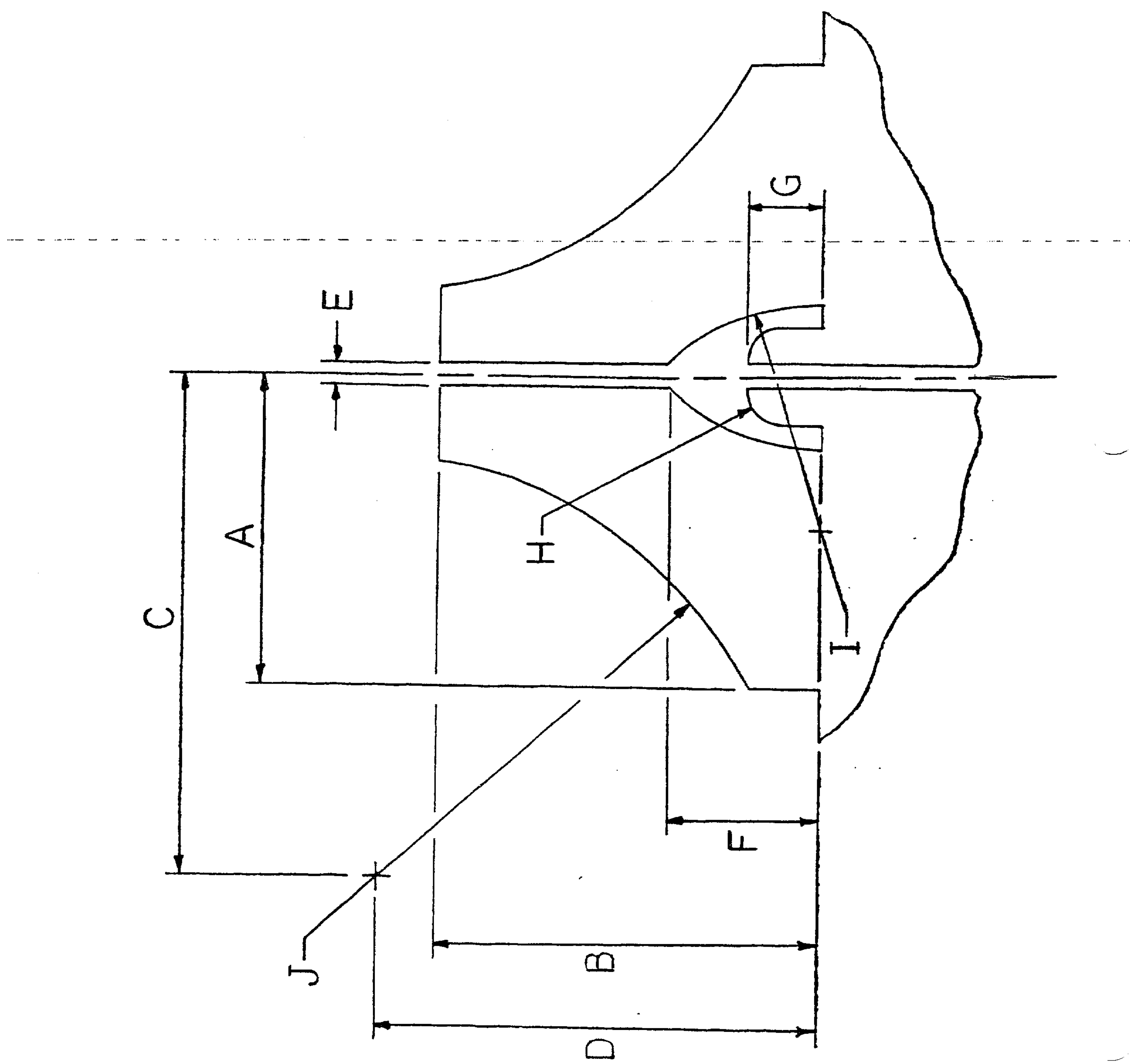


Figure Q-1.3

Vane Dimensions



Appendix H

Documented Response to

RAI-2 Dated October 21, 1998

REQUEST FOR ADDITIONAL INFORMATION (RAI)
ON THE RESPONSES TO RAI FOR ADDENDUM 1 TO BAW-10199P
FOR APPLICATIONS TO THE MARK B11 AND MARK BW17 MSM DESIGNS

1. *The response to Question 3 dated February 23,1998, states that no bias was found when the B11 and BW17-MSM data bases were analyzed with the BWU-Z correlation, and only the "average levels" were different. Please provide information supporting this conclusion, in the form of*

(a) plots of the BWU-Z correlation results (with $F_{B11} = 1.0$ *and* $F_{MSM} = 1.0$*) for the two data bases, showing measured-to-predicted CHF ratio versus mass velocity, pressure, and equilibrium quality at CHF (as already presented in Figures E-1 through E-3 and Figures F-1 through F-3 for the BWU-Z correlation with* $F_{B11} = 0.98$ *and* $F_{MSM} = 1.15$ *in Addendum 1 to BAW-10199P-A).*

b) if sets of replicate or near-replicate data points can be identified between the BW17 data base and the B11 data base, and between the BW17 data base and the BW17-MSM data base, present plots with measured CHF as the independent variable versus predicted CHF obtained

1) *using the BWU-Z correlation with* $F_{B11} = 0.98$ *and with* $F_{B11} = 1.0$ *for each replicate data point common to the BW17 and B11 data bases*

2) *using the BWU-Z correlation with* $F_{MSM} = 1.15$ *and with* $F_{MSM} = 1.0$ *for each replicate data point common to the BW17 and BW17-MSM data bases*

RESPONSE 1

For any given CHF test (i.e., any given physical configuration), the independent variables are system pressure (Psys), inlet mass velocity (Gin) and inlet temperature (Tin). These variables are set for each data point and the dependent variable, the test section power (Q), is slowly increased until the DNB event is observed. In analysis with a CHF correlation, the independent variables are transformed by analysis with a thermal-hydraulic computer code (LYNXT) to local thermal-hydraulic conditions of pressure (P), mass velocity (G) and thermodynamic quality (X) at the axial location of the DNB event. The dependent variable becomes the local axial heat flux (q").

Once a CHF correlation and its data base are established for a given design (here the Mark BW17 with the BWU-Z correlation), an evaluation of the applicability of this established correlation can be made to any other data base supporting a new or different design. When performing this evaluation, the data points from the new data base common to the established data base are first compared to see if the established correlation accurately describes the new design. This is what was done in the case of the Mark B11 and Mark BW17-MSM designs. Independent variable data ranges common to all three data bases were

included. This technique is essentially a comparison between replicate data sets (not individual data points) as far as the independent variable ranges are concerned.

To answer both parts of this question, the replicate data sets were reconstructed for the three data bases: the Mark BW17, the Mark B11 and the Mark BW17-MSM. These sets consisted of data with the discrete nominal pressures of 1500, 1800, 2100 and 2400 psia and nominal mass velocities of 1.0, 1.5, 2.0, 2.5 and 3.0 million pounds per hour per square foot common to all three data bases. The replicate data base for the Mark BW17 data base consisted of 411 of the original 530 data, for the Mark B11, 177 of the original 216 data and for the Mark BW17-MSM, 62 of the original 76 data.

RESPONSE 1a

Figures Q1a-1 and Q1a-2 show summary bias plots of the Mark B11 replicate data set with F_{B11} = 0.98 and 1.0 respectively. Figures Q1a-3 and Q1a-4 show these summary bias plots for the Mark BW17-MSM replicate data set with F_{MSM} = 1.15 and 1.0 respectively. Finally, for reference, Figure Q1a-5 shows the summary bias plots for the replicate Mark BW17 data base of 411 data. It should be noted that the change in F_{B11} = 0.98 to 1.0 merely raises each M/P value on the summary bias plots by 2 percent uniformly (i.e., the predicted CHF, P in the M/P value, is multiplied by 0.98). Likewise the change in F_{MSM} = 1.15 to 1.0 lowers the values uniformly by 15 percent. F_{B11} and F_{MSM} are simple normalization factors. The corresponding normalization factor for the Mark BW17 data base is, of course, 1.0. Thus any bias with respect to the independent variables can be seen regardless of the F_{B11} or F_{MSM} values.

Examination of these figures shows that, over the replicate local condition independent variable ranges (1500 to 2400 psia, 1.0 to 3.0 million pounds per square foot and −10 to +30 percent equilibrium quality), the bias plots are grouped around a constant horizontal average value. This horizontal average value is the Mean M/P CHF Ratio shown on each individual summary bias plot. Further, all of the individual M/P values for all plots are well within the horizontal dotted lines denoting +/- 3.5 standard deviations of the specific M/P data base.

Finally, the coefficient of variation is the measure of the precision of the correlation. For the Mark B11 data the coefficient of variations are actually lower than the original Mark BW17 data base (for which the BWU-Z correlation was optimized), and only slightly higher for the Mark BW17-MSM data base.

These three observations (grouping around a horizontal line, individual values within normal uncertainty limits and coefficients of variation comparable to that of the original correlation data base) indicate that a simple normalization factor applied to the base correlation (the F_{B11} and F_{MSM} multipliers) accurately describes the data bases of these new designs.

RESPONSE 1b

Figures Q1b-1 and Q1b-2 show measured CHF versus predicted CHF plots of the Mark B11 replicate data set with F_{B11} = 0.98 and 1.0 respectively. Figures Q1b-3 and Q1b-4 show these plots for the Mark BW17-MSM replicate data set with F_{MSM} = 1.15 and 1.0 respectively. Finally, for reference, Figure Q1b-5 shows the measured versus predicted plot

for the replicate Mark BW17 data base of 411 data. Again it should be noted that the change in F_{B11} or F_{MSM} merely raises or lowers predicted CHF value by a given percentage and that the corresponding normalization factor for the Mark BW17 data base is 1.0.

Examination of the plots with normalization factors (Figure Q1b-1 and Figure Q1b-3) shows that the individual points are grouped evenly about the 45 degree inclined line (where the measured CHF exactly matches the predicted CHF) and all values are well within the +/- 3.5 standard deviation limits. For the unnormalized plot with F_{B11} = 1.0 (Figure Q1b-2), the average individual value is below the 45 degree line, while for Figure Q1b-4 (with F_{MSM} = 1.0) it is well above it. This deviation from scatter centered about the 45 degree line indicates the need for a normalization factor (i.e., F_{B11} and F_{MSM} respectively). Finally, the normalized measured versus predicted plot (utilizing F_{B11} = 0.98 and F_{MSM} = 1.15) show no bias with respect to absolute CHF level. That is, the spread about the 45 degree line is relatively constant (on a percentage basis) over the whole range of measured heat fluxes.

2. The data base for the BW17-MSM fuel design is extraordinarily small (only 76 data points) and of limited range, covering only 1000 to 2400 psia on pressure, and 1.0 to 3.2 Mlbmlhr-ftz. The extension down to 1000 psia is based on only 3 data points at pressures below 1500 psia, and the range of equilibrium quality at CHF is 0.31 or lower, except for a single point at 0.48. What is the intended range of application of the BWU-Z correlation with F_{MSM} *=1.15? If thls range of application exceeds the range of conditions spanned by the data base for BW17-MSM fuel design, what is the justification for this extrapolation?*

RESPONSE 2

The Mark BW17-MSM is considered, from a CHF view, to be a sub-design of the original Mark BW17, with the difference that it is to be applied at half the normal grid spacing in order to raise the overall CHF level. The CHF performance should be that of the Mark BW17 grid, but at a higher level in the shortened grid span. This is the reason for inclusion of only one test (76 data) for the Mark BW17-MSM. The one test was considered to be sufficient to establish a CHF performance multiplier resulting from the reduced grid spacing.

As stated on page E-5 of the addendum, the range of application for the Mark BW17-MSM is shown in Table 4-1 of BAW 10199P-A (page 4-5). This includes application of the more conservative design limits of 1.20 between 700 and 1000 psia and 1.59 below 700 psia. The justification for the 1.19 design limit above 1000 psia for the Mark BW17-MSM is provided in the response to question 1a and 1b above. The justification for the use of the conservatively higher Mark BW17 design limits at and below 1000 psia is twofold. First, as discussed in the February 23 question responses (T. A. Coleman to Document Control Desk, GR158.doc, February 23, 1998), the duplication of the Mark BW17 mixing vane and vane pattern in the Mark BW-17-MSM design would indicate that CHF performance would have the same sensitivity to changes in the independent variables (P, G and X). This is demonstrated in the response to questions 1a and 1b above for the normal PWR operating pressure range of 1500 to 2400 psia. Secondly, the three MSM data at 1000 psia with F_{MSM} = 1.15 have an average M/P value of 1.11 (11 percent conservative). This indicates that the performance of the Mark BW17-MSM at lower than normal pressures (less than 1500 psia) is conservatively predicted by the modified BWU-Z correlation and thus the conservative

lower pressure design limits developed for the Mark BW17 are applicable to the Mark BW17-MSM.

3. *Report BAW-10229P, referred to in the response to Question 7, is not an approved topical report. Describe the tests done for both the 5-by-5 and the 17-by-17 full spacer grids and the derivation of the form loss coefficients based on the experimental data. Provide the details to clarify that the Mark B11 spacer grid was tested and the results show that the form loss coefficient based on the experimental data is identical to that of the BW17 spacer grid.*

RESPONSE 3

Pressure drop tests to determine overall (grid) form losses were performed on both the Mark BW17 (17x17 matrix) and the Mark B11 (15x15 matrix). No pressure drop tests were performed on 5x5 CHF test grids. The grid form losses are developed from a series of flow tests performed in the Control Rod Drive Line (CRDL) test facility at the B&W Alliance Research Center. The CRDL is a closed loop facility for flow testing full size fuel assemblies. It can produce coolant flow, pressures and temperatures representative of those occurring during reactor operation. Form loss coefficients for the fuel assembly components (including the spacer grids) are developed by measuring the pressure drop across these components. When friction pressure drop is subtracted, the form loss coefficient is simply the pressure drop divided by the velocity head. Pressure drop and flow testing data is analyzed in detail in calculational files supporting the specific topical reports for each design (BAW-10220P, Mark-BW Fuel Assembly Application for Sequoyah Nuclear Units 1 & 2, for the Mark BW17 and BAW-10229P, Mark-B11 Fuel Assembly Design Topical Report, for the Mark B11).

In Response 7 to the February 23 questions, the method for derivation of the individual subchannel form loss coefficients was described. The values used in the Mark B11 analysis (Table E-2 of the Topical) were based on the Mark BW17 values, because no Mark B11 values were available at that time. This was felt to be a reasonable assumption since the Mark B11 is a scaled up version of the Mark BW17 and since form loss coefficients are dimensionless numbers. It was further known (as stated in Response 7) that calculated CHF values are quite insensitive to the magnitude of the overall form loss coefficient. This has been confirmed for the Mark B11 analysis by reducing the overall 5x5 CHF grid form loss to the measured Mark B11 value {( ).}^{c,d,e} When this was done the mean M/P value of the 32 data for test 26.0 changed from { }^{c,d,e}. The standard deviation remained constant at { }^{c,d,e} The change of less than { }^{c,d,e} percent in the mean M/P value (for a 10 percent change in the overall form loss coefficient) confirms the insensitivity of the overall form loss value on CHF and confirms the validity of the form loss coefficients used in the Mark B11 analysis.

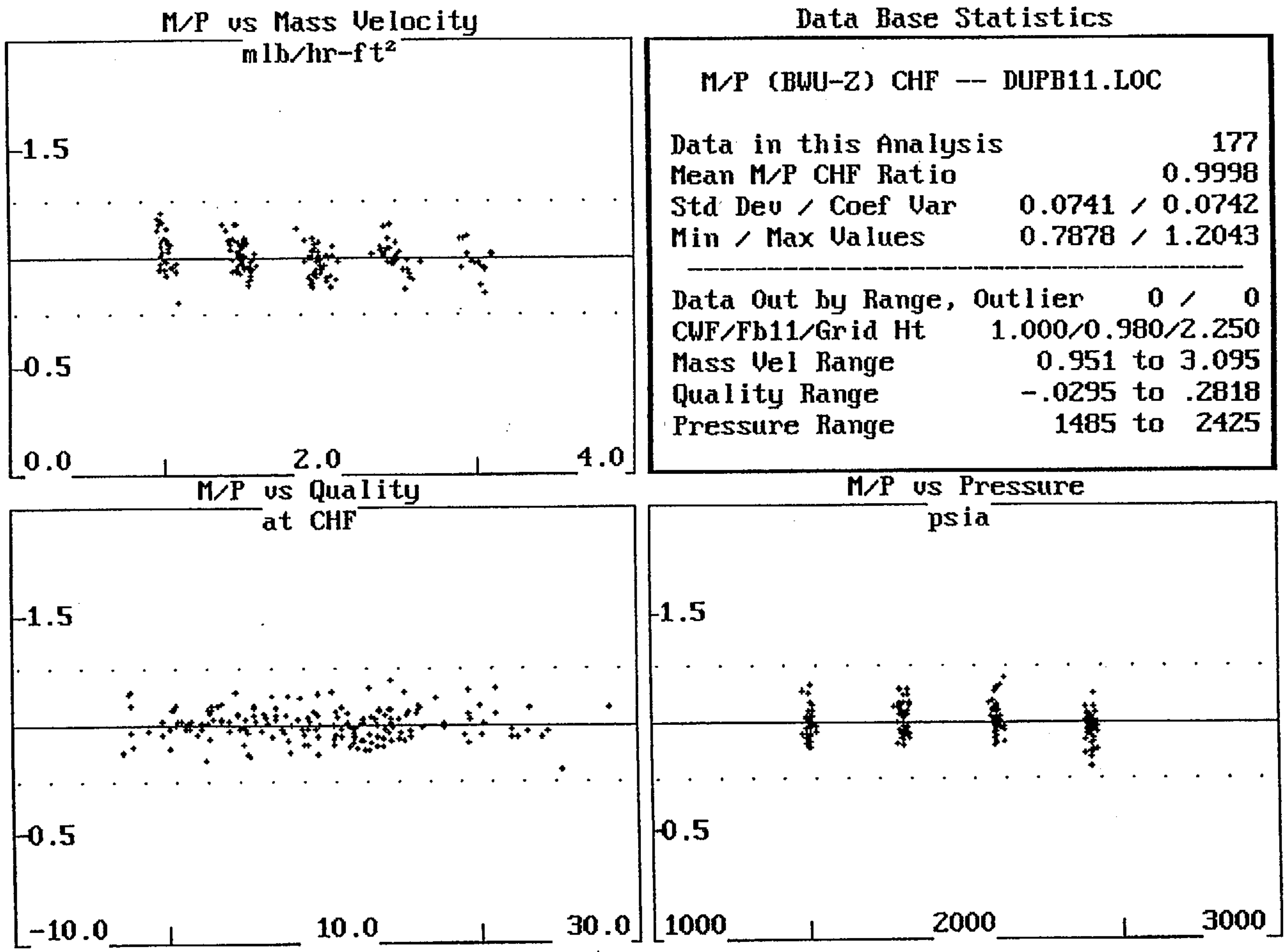


Figure Q1a-1
Mark B11 Replicate Data Base with $F_{B11} = 0.98$

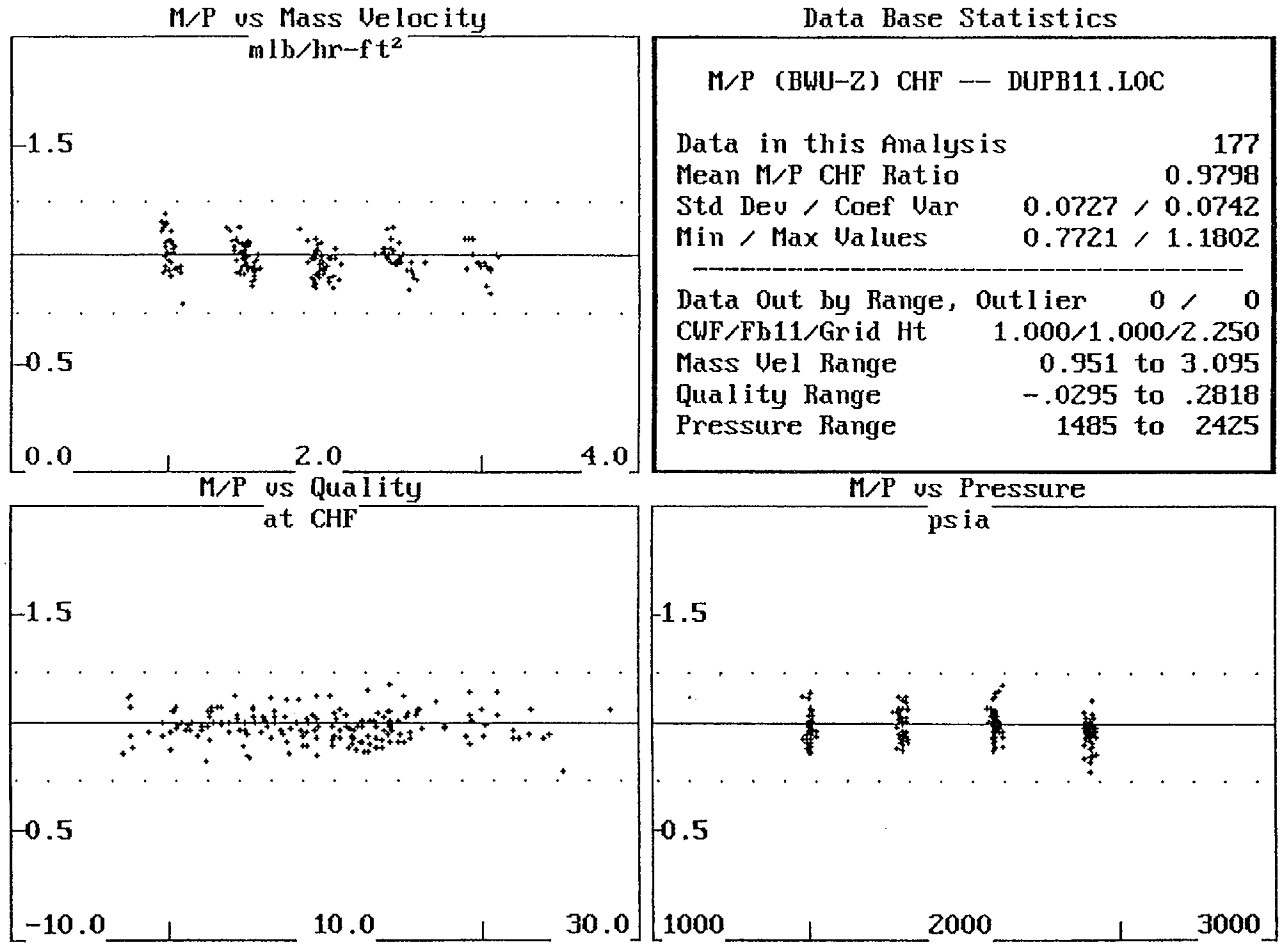


Figure Q1a-2
Mark B11 Replicate Data Base with $F_{B11} = 1.0$

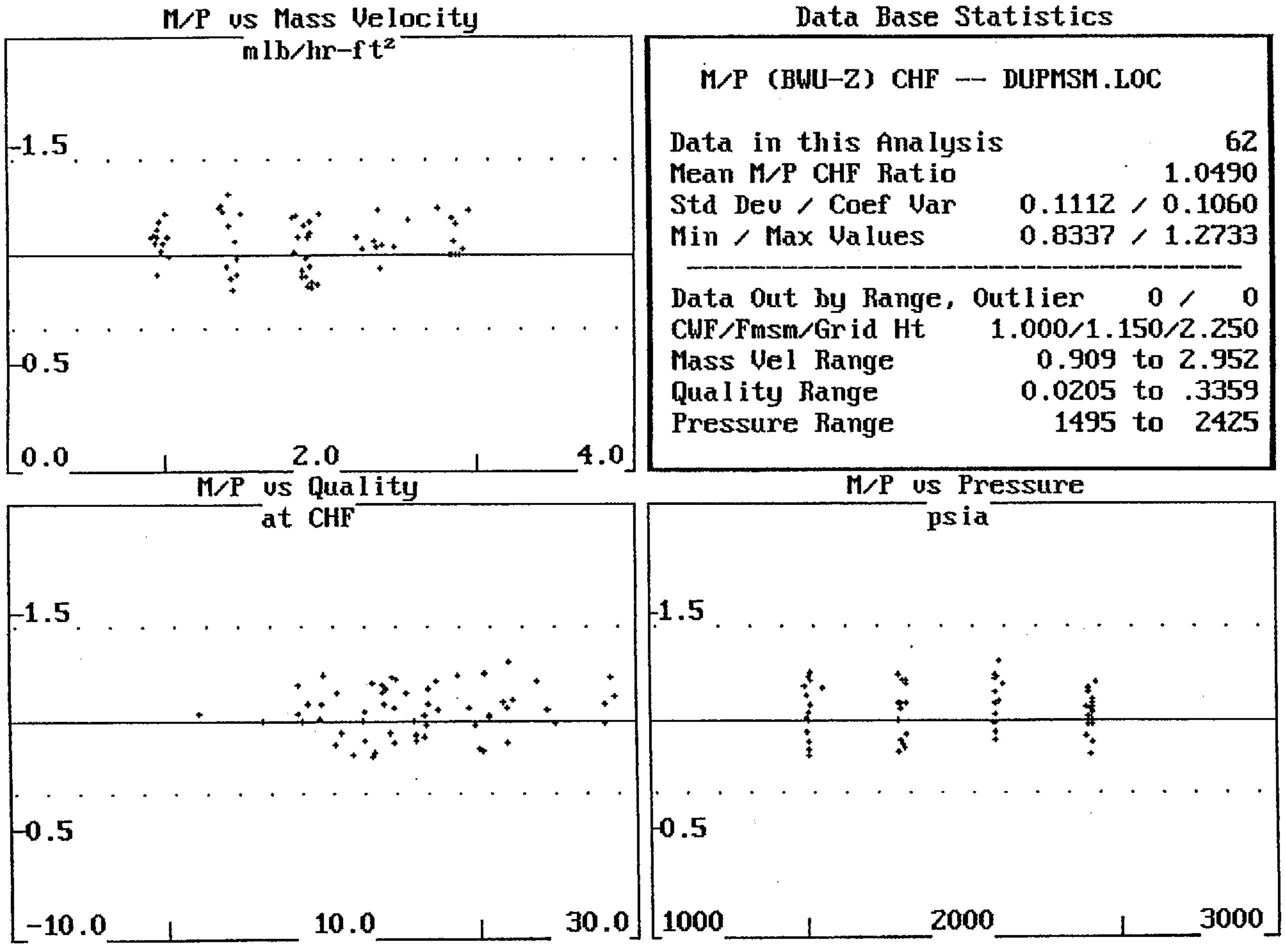
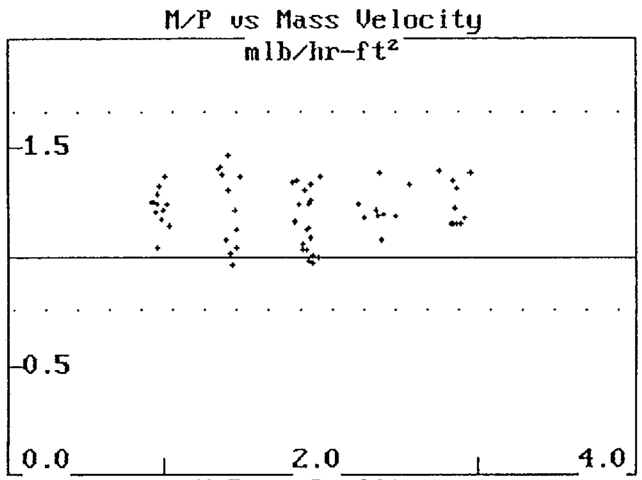


Figure Q1a-3
Mark BW17-MSM Replicate Data Base with F_{MSM} = 1.15

Figure Q1a-4

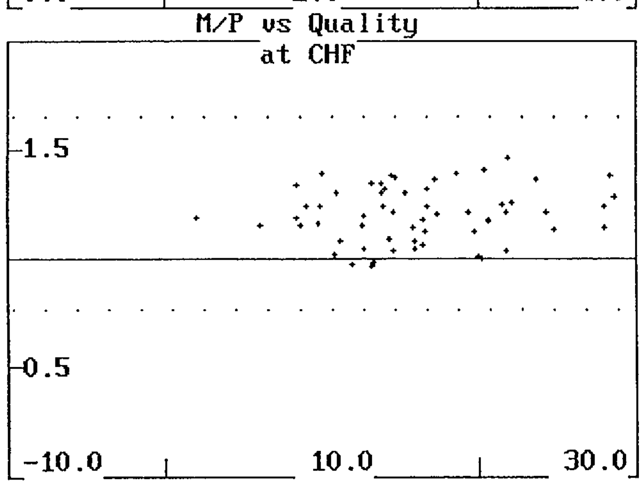
Mark BW17-MSM Replicate Data Base with F_{MSM} = 1.0

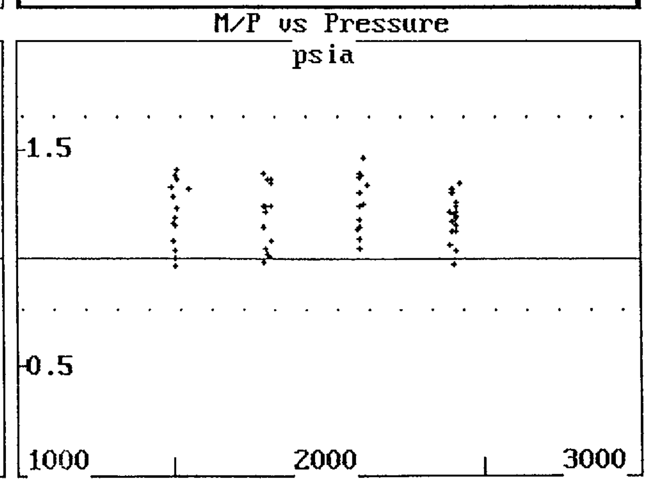


Data Base Statistics

M/P (BWU-Z) CHF -- DUPMSM.LOC

Data in this Analysis	62
Mean M/P CHF Ratio	1.2064
Std Dev / Coef Var	0.1279 / 0.1060
Min / Max Values	0.9588 / 1.4643
Data Out by Range, Outlier	0 / 0
CWF/Fmsm/Grid Ht	1.000/1.000/2.250
Mass Vel Range	0.909 to 2.952
Quality Range	0.0205 to .3359
Pressure Range	1495 to 2425





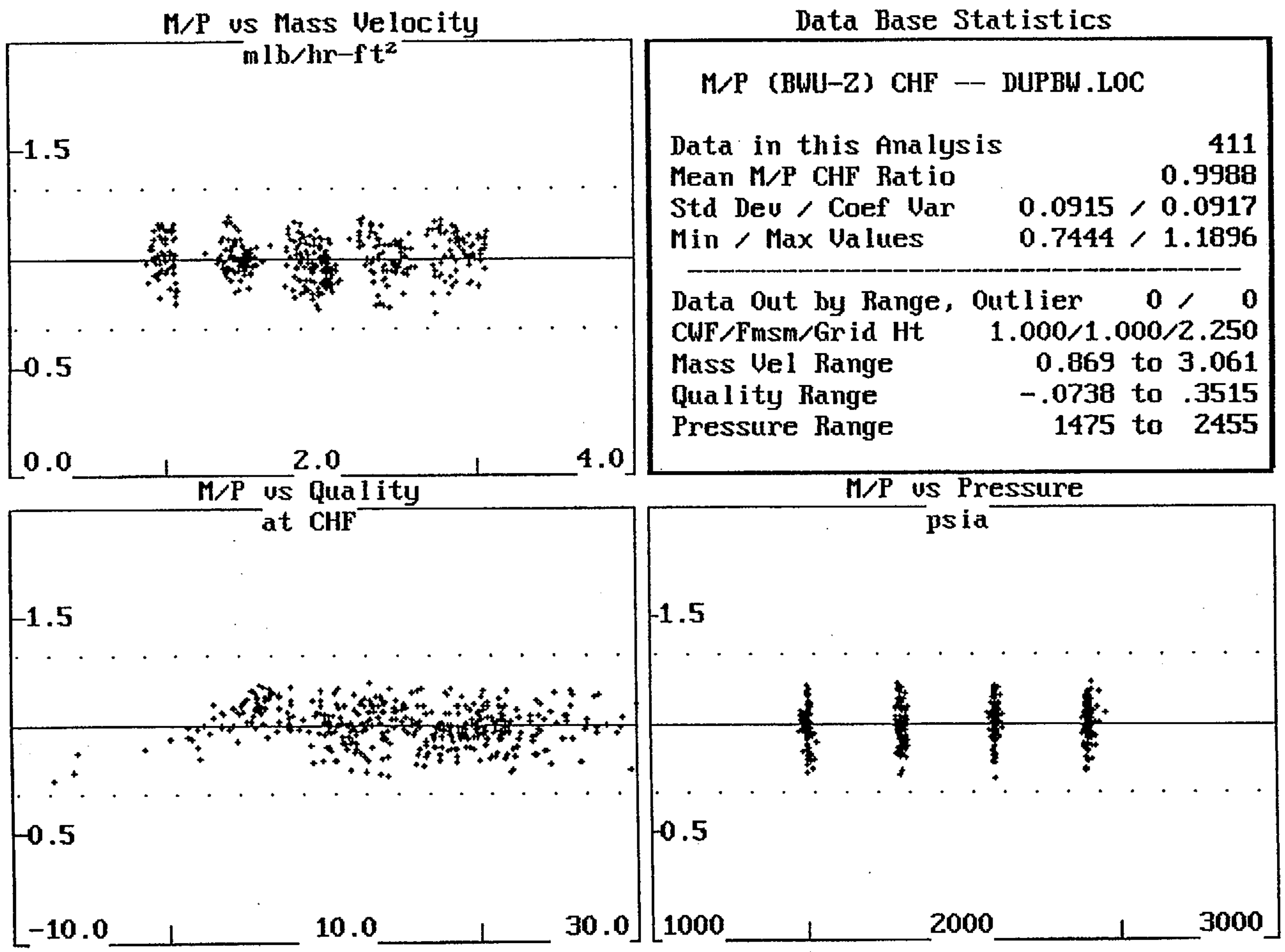


Figure Q1a-5
Mark BW17 Replicate Data Base

Figure Q1b-1
Mark B11 Replicate Data Base with $F_{B11} = 0.98$

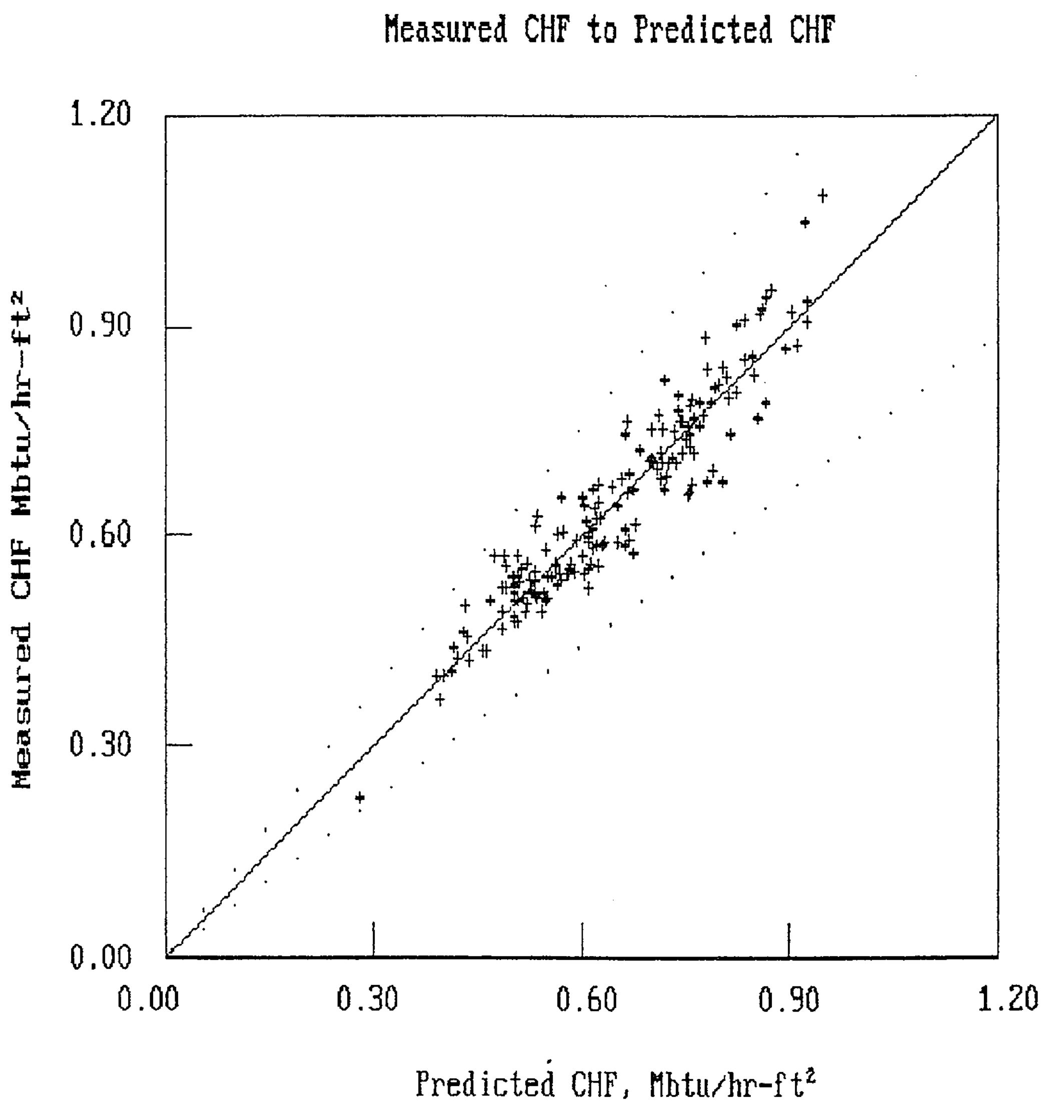


Figure Q1b-2
Mark B11 Replicate Data Base with $F_{B11} = 1.0$

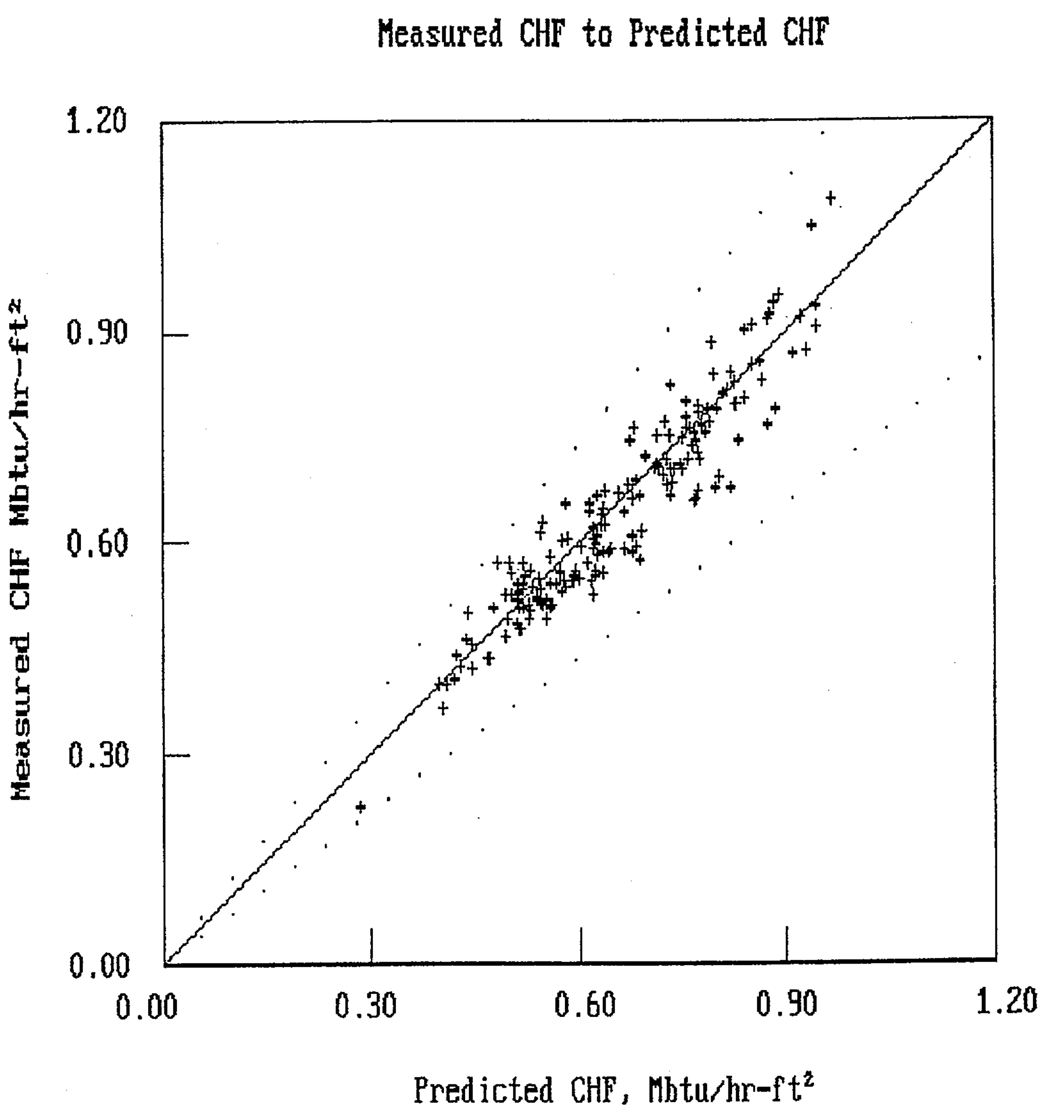


Figure Q1b-3
Mark BW17-MSM Replicate Data Base with $F_{MSM} = 1.15$

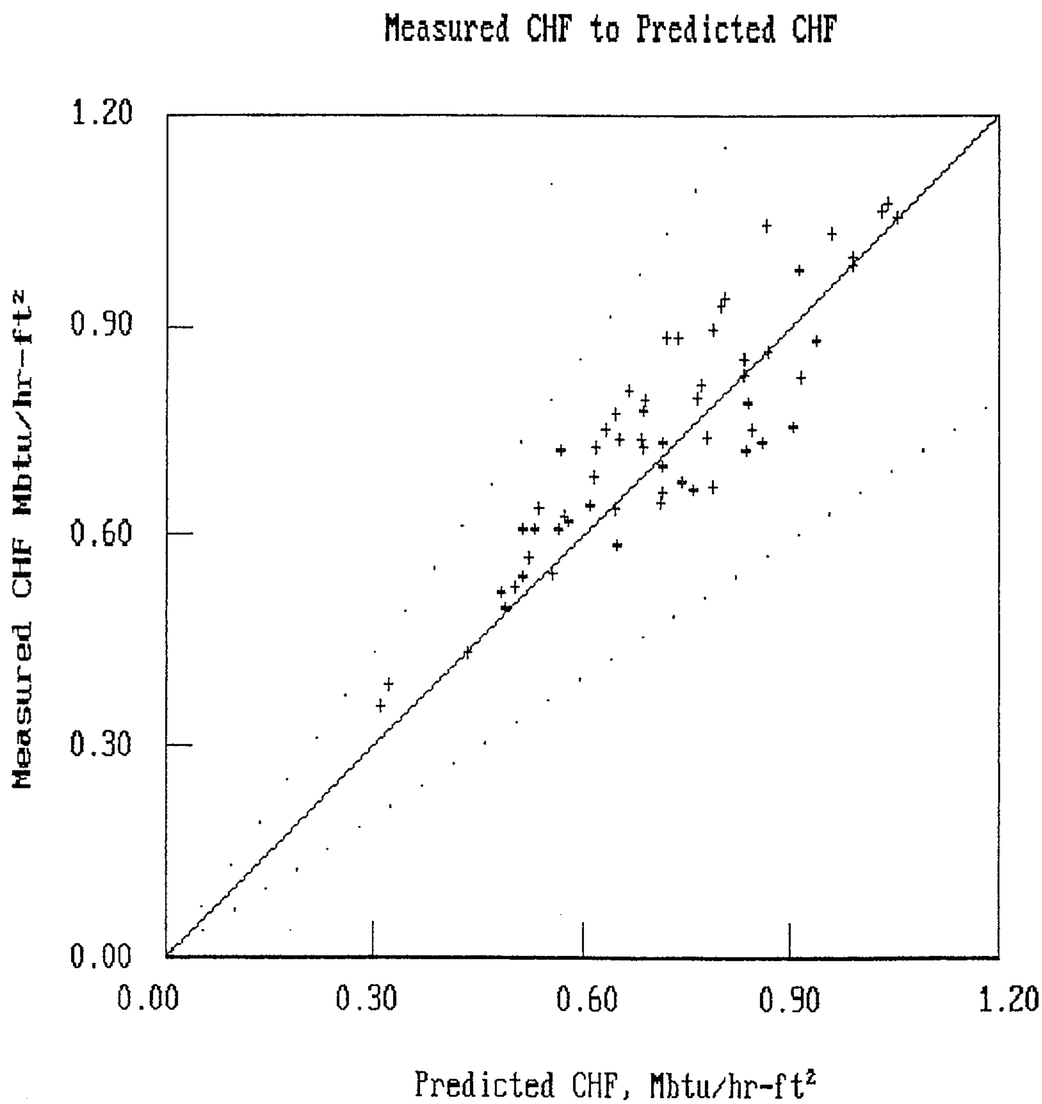


Figure Q1b-4
Mark BW17-MSM Replicate Data Base with $F_{MSM} = 1.0$

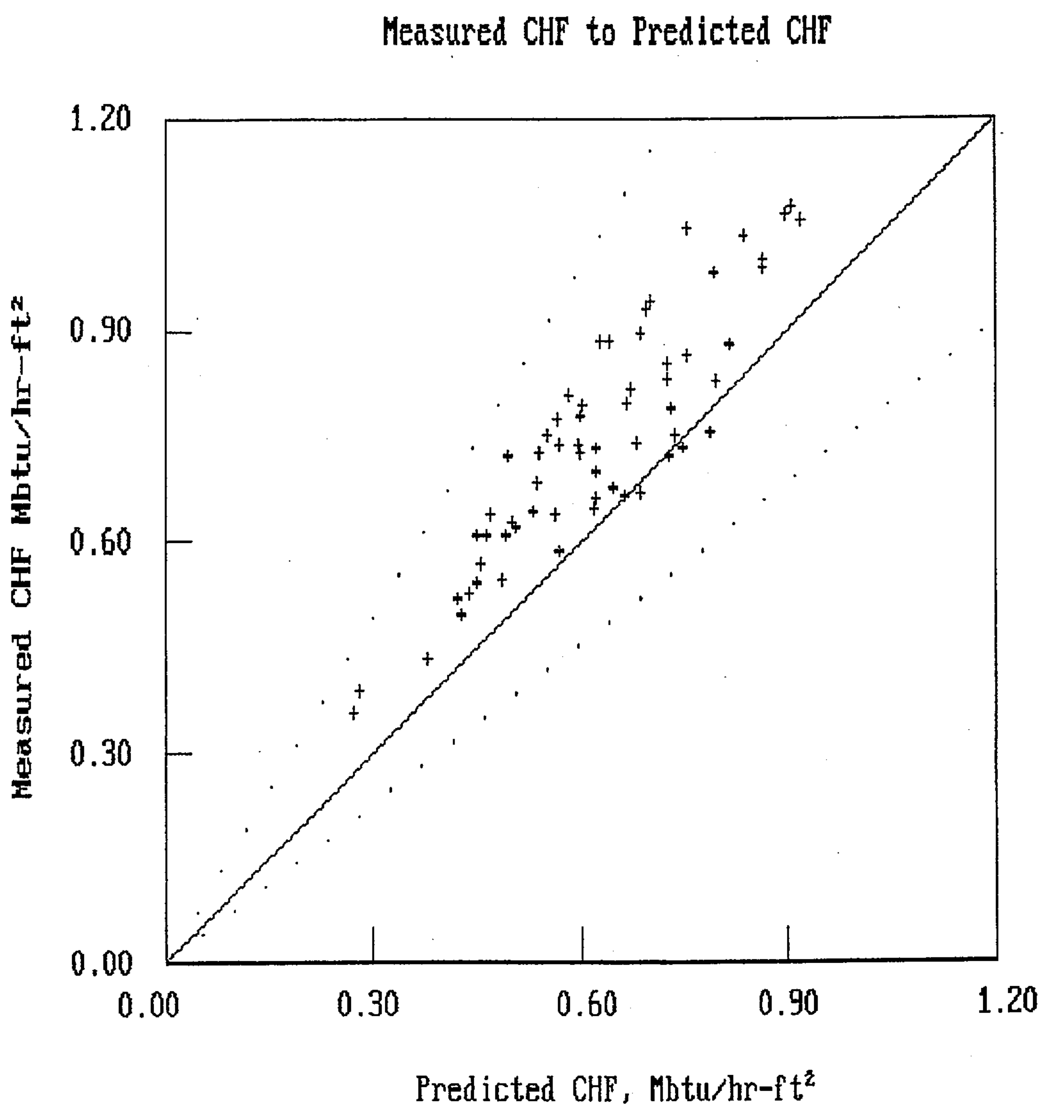
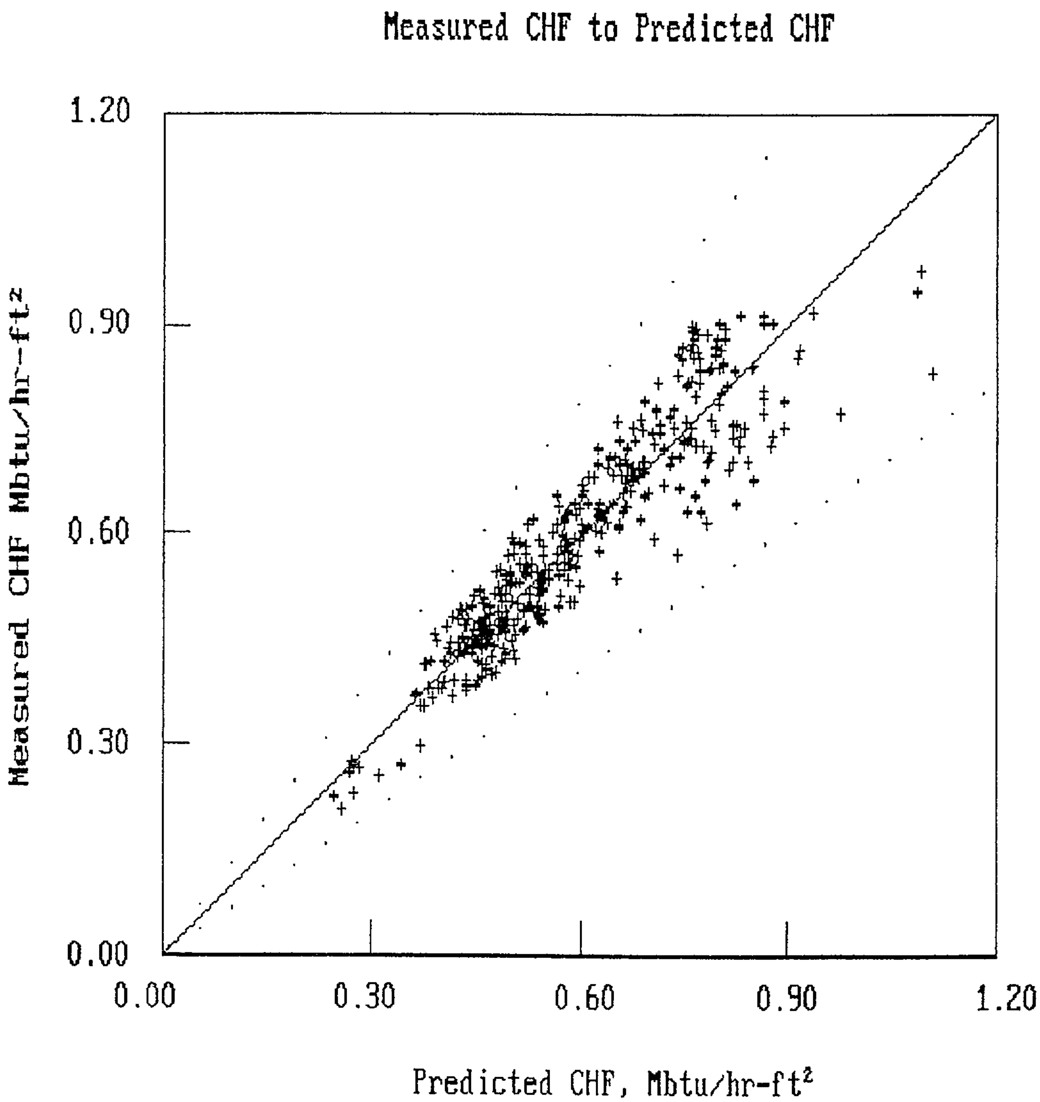


Figure Q1b-5
Mark BW17 Replicate Data Base



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