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Should our acceptance criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, applicants referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued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,

/***RA/***

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

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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 <u>CONCLUSION</u>

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
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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.