framatome

Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel

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Revision 2, Q3NP
Revision 0

Topical Report

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FRAMATOME TRADEMARKS

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	All	Initial Issue

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Nomenclature

Acronym	Definition
AFA 3G	Advance Fuel Assembly 3rd Generation
B&W	Babcock and Wilcox
CE	Combustion Engineering
DNBR	Departure from Nucleate Boiling Ratio
GCR	Gap Closure Ratio
GWd/mtU	Giga-Watt days per metric ton Uranium
HMP	High Mechanical Performance
HTP	High Thermal Performance
IFM	Intermediate Flow Mixing
IMG	Intermediate Mixing Grid
LHGR	Linear Heat Generation Rate
MDNBR	Minimum Departure from Nucleate Boiling Ratio
MSMG	Mid-Span Mixing Grid
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
TR	Topical Report
UDL	Upper Design Limit
W	Westinghouse

INTRODUCTION

The United States Nuclear Regulatory Commission (NRC) provided a request for additional information (RAI) regarding the topical report BAW-10227P Revision 2 (Reference 1) in Reference 2. The response to RAI 3 is provided in Section 1.0.

1.0 RAI 3

QUESTION:

Please submit the table and plot of the fuel rod bow database, along with lines for all fuel assembly designs that may use M5 cladding at the increased burnup limits described in this Topical Report (TR). Please include all available data collected on M5 rod bow, using different colors/markers for different fuel designs.

RESPONSE:

Since the development of Framatome's fuel rod bow predictive models in References 3 and 4, additional fuel rod water channel gap measurements have been obtained at various [ ]. The expanded dataset includes a total of [ ], as summarized in Table 1-1, with design variations including [ ]. The variations in the historical designs associated with the dataset are discussed below for background information.

Data obtained from fuel rods within 15x15 arrays have been used at B&W and Westinghouse units, in the U.S. and Europe, with [ ]. Design variants have included [ ]. Data has also been collected on designs with [ ].

Fuel rod bow measurements from designs with 17x17 arrays at B&W and Westinghouse units, in both the U.S. and Europe, have been obtained on fuel rods [ ]. Data on fuel rods with [ ]. Other designs utilized [ ]. Advanced designs contained [ ]. Grid designs evolved to [ ]. Assembly designs with [ ]. Data obtained from the latest Framatome GAIA design includes [ ].

Fuel rod bow data from an Advanced HTP design at a Combustion Engineering (CE) 14x14 unit utilized [ ].

The [ ]. The data consist of [ ] standard deviations of the fuel rod-to-fuel rod (FR-FR) water channel gap measurements, as defined within Supplement 1 of Reference 3 and Reference 4. [ ].

With the expanded database of fuel rod water channel gap data, Framatome has developed a new fuel rod bow correlation that is [ ].

The [ ] standard deviations of the fuel rod water channel gap measurements, as defined within Supplement 1 of Reference 3, are considered to be the change in gap closure, or fuel rod bow for the span, ΔC. [

]. This data was converted to gap closure ratio (GCR) by dividing the change in gap closure by the nominal as-built gap, C_o. The gap closure ratio, $\Delta C/C_o$ is dimensionless and can be applied regardless of design. The gap closure ratio for each measurement is [

] in keeping with U.S. NRC guidance, as explained within Section 3.3 of Reference 3. This [ ] gap closure ratio data is presented in Figure 1-3.

[

]

Data for all designs was pooled according to array. Designs of the same array have similar spacer grid span lengths and fuel rod cross sections. Differences between fuel rod materials were investigated. Figure 1-4 provides Zircaloy-4 and $M5_{Framatome}$ gap closure ratio versus fuel assembly average burnup data for all designs. [

].

The fuel rod gap closure correlation was developed using the combined U.S. and European 17x17 data which is considered bounding of all Framatome fuel designs and arrays. The fuel rod gap closure correlation is applicable as long as subsequent changes do not affect key characteristics with respect to fuel rod bow. The key characteristics of these designs with respect to fuel rod bow are:

[ ]

[ ]

Framatome plans to continue to monitor the performance of fuel rod gap closure as designs achieve higher burnups, consistent with Section 14.0 of Reference 1. Data may be obtained at fuel assembly average burnups [ ], for increased utilization of new designs (e.g. GAIA), or new design features (e.g., Q12 guide tubes and grids).

The best-estimate fit of the gap closure ratio data is:

[ ] Eqn. (1),

where BU is the fuel assembly average burnup in GWd/mtU.

An upper bounding gap closure ratio determined by [ ] to account for batch-to-batch variation, consistent with Section 3.3 of Supplement 1 of Reference 3, is:

[ ] Eqn. (2),

where BU is the fuel assembly average burnup in GWd/mtU.

[

]

[ ] Eqn. (3),

where BU is the fuel assembly average burnup in GWd/mtU.

The UDL for the gap closure ratio is applicable for fuel assembly average burnups
[

].

[

].

[

].

The following change to Reference 3 is necessary when determining the reduction in MDNBR for fuel rod gap closures [ ] within Equation 6.2 of Reference 3, Supplement 1, as revised by Supplement 2 (Equation 4.2) and updated in the response to Question 16 of Supplement 4 for the calculation of δ_B, which is the fractional reduction in MDNBR due to fuel rod bowing.

Equations for reduction in MDNBR from Reference 3 are as follows:

[ ]

Equation 6.2 is replaced by:

[ ]

The following change to Reference 3 is necessary when determining the fuel rod bow augmentation of LHGR penalties. The UDL_{GCR} as defined by Eqn. (3) will be used in place of [

]

within Equations 5.1 and 5.2 of Reference 3, Supplement 1 as updated by the response to Question 20 of Supplement 4 of Reference 3.

Equations for the determination of the change in flow area as a function of fuel rod bow (A/A_o) from Reference 3 are as follows [

]:

[ ]

These equations are replaced by:

[ ]

Table 1-1: Fuel Rod Bow Database

[ ]

Figure 1-1: Fuel Rod Water Channel Gap [ ] Standard Deviations vs. Burnup

[

]

Figure 1-2: 17x17 Fuel Rod Water Channel Gap [ ]
Standard Deviations vs. Burnup

[ ]

Figure 1-3: Gap Closure Ratio Data Adjusted to Core Operating Temperature

[ ]

Figure 1-4: M5Framatome and Zircaloy-4 Gap Closure Ratio Data Comparison

[ ]

Figure 1-5: Gap Closure Ratio Correlation

[ ]

Figure 1-6: Gap Closure Ratio [

]

2.0 REFERENCES

1. BAW-10227P Revision 2, Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel, December 2019
2. Letter, Ngola Otto (NRC) to Gary Peters (Framatome Inc.), "Request for Additional Information Regarding Framatome Inc. Topical Report, BAW-10227, Revision 2, 'Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel' (EPID L-2019-TOP-0054)," August 21, 2020
3. XN-75-32(P)(A) Supplements 1, 2, 3 & 4, Computational Procedure for Evaluating Fuel Rod Bowing, October 1983
4. BAW-10147P-A, Revision 1, Fuel Rod Bowing in Babcock & Wilcox Fuel Designs, May 1983

3.0 BAW-10227P REVISION 2 MARKUPS

Section 11.4 of Reference 1 will be replaced in its entirety by the following text:

11.4 Fuel Rod Bowing

Fuel rod bow is driven by the irradiation growth of the fuel rods and friction with the supporting fuel assembly cage structure. Since the development of the fuel rod bow correlation in Reference [24], additional fuel rod water channel gap measurements have been obtained at [

]. The gap closure ratio for each measurement [

] in accordance with Section 3.3 of Reference [24]. The equation for the upper design limit (UDL) for gap closure ratio (GCR) is:

[ ] 11-4,

where BU is the fuel assembly average burnup in GWd/mtU, [

].

Figure 11-4 provides a plot of the correlation with the corresponding data identified by fuel design.

The approved performance and penalties established in Reference [24] apply to the $M5_{Framatome}$ cladding designs, with the following exceptions:

> The effects of fuel rod gap closure are included in the departure from nucleate boiling (DNB) analysis by a reduction in Minimum value for the Departure from Nucleate Boiling Ratio (MDNBR) [ ] within Reference [24] for the calculation of δ_B, the fractional reduction in MDNBR due to fuel rod bowing. Section 6.2 of Supplement 1 of Reference [24] contains the relationship between gap closure ($\Delta C/C_o$) and the fractional reduction in MDNBR due to fuel rod bowing (δ_B). Supplement 2 of Reference [24] introduces [ ]. The updated Equation 6.2 is provided in the response to Question 16 within Supplement 4 of Reference [24].
>
> When determining the fuel rod bow augmentation of Linear Heat Generation Rate (LHGR) penalties, [ ] within Equations 5.1 and 5.2 of Supplement 1 as updated by the response to Question 20 of Supplement 4 in Reference [24].

The fuel rod gap closure correlation is applicable to Framatome fuel designs as long as subsequent changes do not affect key characteristics with respect to fuel rod bow. The key characteristics of these designs with respect to fuel rod bow are:

[ ]

[ ]

[ ].

This methodology for fuel rod bow is consistent with Reference [3].

Figure 11-4: M5$_{\text{Framatome}}$ Fuel Rod Gap Closure Ratio