Pacific Northwest National Laboratory

Technical Report: GEH Marathon-Ultra Control Blade Finite Element Analysis Calculations

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1.0 Introduction

This technical letter report details the PNNL evaluation of the finite element analyses (FEA) contained in "Marathon-Ultra Control Rod Assembly," NEDE-33284P, Supplement 1, Revision 0, January 2010. As defined in Section 2 of NEDE-33284P, Supplement 1, the only difference between the Marathon-Ultra (M-Ultra) and the Marathon-5S (M-5S) is the absorber section neutron absorber components. The outer structure of the control rod, consisting of the handle, absorber tubes, tie rod, and velocity limiter are identical. Further, the component materials and manufacturing processes, including welding, are exactly the same. Because of these limited changes, many of the FEA results reported in NEDE-33284P, Revision 2, October 2009 for the M-5S are still applicable to M-Ultra and the scope of this review was limited to the FEA models that were affected by the design changes.

The difference between the two designs is the internal configuration of the absorber tubes. The M-Ultra has thinner boron carbide capsule walls and some of the absorber tubes are filled with full length hafnium rods instead of boron carbide capsules. The changes to the boron carbide wall thickness affect the heat transfer scenario, which affects the peak temperature, the helium release rate, and the internal absorber tube pressure. The change to the internal components affects the total control blade weight, which affects the lifting load scenario and handle stresses. The FEA models that are not affected by these changes are noted in Table 3-24 of NEDE-33284P, Supplement 1 as being identical. The External Pressure + Channel Bow Lateral Load model is unaffected by the material or conditions inside the absorber tube because the model conservatively ignores internal pressure. The Internal Pressure model determines the maximum burst pressure based on the pressure required to cause the absorber tube to reach the material ultimate strength. One half of this burst pressure is considered to be the maximum allowable absorber tube pressure, which is used to determine the Pressurization Stresses in the absorber tube and the stresses occurring in the Combined Internal Pressure + Fuel Channel Bow Induced Bending analyses. This analysis strategy establishes a maximum internal pressure threshold, and evaluates stresses at that maximum allowable condition. Because the outside tube structure does not change, these models are applicable to both the M-5S and M-Ultra.

Section 2.0 describes the review process and history. Section 3.0 discusses the thermal model. Section 4.0 discusses the lifting load model. Section 5.0 summarized the conclusions of this review.

2.0 Review Process

GEH provided all of the FEA models associated with the M-Ultra in ANSYS input file format. The reviewer was able to run the models successfully and confirm that all results matched those reported in the topical report and to determine that the models were free of any fundamental modeling errors. Access to the model input files also allowed the reviewer to consider the effects of small modifications to the analysis methodology, such as modeling the lifting loads with three-dimensional structural models instead of two-dimensional, and the potential effects of GE's heat generation distribution assumptions on the thermal model peak temperature results.

Some points of the GEH analysis methodology were not clear from the models or available topical reports. The local heat generation rates specified in the thermal model is one example. Confirmatory calculations using the standard Jens-Lottes correlation were performed by the reviewer and matched the outside temperature of the absorber tube predicted by the GEH model, but it was not able to confirm the specific heat generation distribution applied to the B4C material. As many issues as possible were resolved before RAI questions were composed, but a number of issues still remained.

In preparation for an audit, open items were identified and transmitted to GEH in May 2011. During the audit at GEH – Wilmington in June 2011 (PNNL participated by phone), these open items were discussed. Information needed to support a safety finding was compiled and RAIs were issued. In a letter dated November 15, 2011 (MFN 11-245), GEH provided responses to the RAIs. These responses are discussed below.

3.0 Thermal Model

GEH uses a 2D ANSYS FEA model to calculate the peak temperature in the control rod. The geometry represents a horizontal section through a single vertical absorber tube. As illustrated in Figure 2-1 of NEDE-33284P Supplement 1, the components are: B4C powder region, capsule wall, helium gap, and absorber tube. The 2D model represents a slice out of the center and is taken to represent the full length of the absorber tube. In this thermal model the heat generation rates are the primary load. Heat is primarily generated within the central B4C powder zone and moves outward to the outside surface of the absorber tube. The amount of heat generated in the B4C is determined in the nuclear analysis code and applied to the ANSYS model as an input. The amount of heat allowed to pass out of the absorber tube into the coolant is derived from the Jens-Lottes correlation.

One important result of this model is the peak B4C temperature. This peak temperature is insensitive to many of the model parameters but is moderately sensitive to the distribution of heat generation in the B4C. The model divides the B4C into eight ring sections that each has its own heat generation rate specified, with a distribution that peaks in the outer ring. When this distribution was flattened to an average heat generation rate applied uniformly across the B4C, the peak temperature increased a notable amount. The results of this confirmatory analysis are presented in Table 1. The "Baseline" case is the D/S Lattice worst case dimension results

reported in Table 3-22 of NEDE-33284P, Supplement 1. The "Average" case uses the same model but sets all the B4C ring multiplication factors to one to explore the significance of the heat generation distribution. The result is an increase in centerline temperature [ ].

GEH's method in this case was to calculate an average heat generation rate for the B4C in the nuclear analysis and assume a particular heat generation distribution (with a minimum at the center and a maximum at the outer radius) in the ANSYS thermal model. This assumption was questioned because the basis of the distribution was not clear, and the previously discussed confirmatory analyses showed the peak and average B4C temperature results were somewhat sensitive to the heat generation distribution. In the June telecon, GEH explained that the distribution was determined for a prior design and the average heat generation from the current Marathon Ultra nuclear analysis (which divided the B4C region differently) was scaled to the old distribution. They committed to justifying this method.

GEH resolved the heat generation distribution issue by showing that when a uniform average heat generation is applied to the nominal D/S lattice configuration the B4C capsule average temperature increases by [ ]. This relatively small increase corresponds to an increased helium release fraction of [ ]. GEH references the boron carbide temperature to helium release relationship plotted in NEDE-33284P-A Revision 2, Appendix C, Figure 1, in stating that the amount of potential error is acceptable. The plot compares the temperature/release relationship to two test cases and it appears that the relationship is vastly conservative compared to the actual test data. The difference between the test case data and the modeled release fraction is on the order of 10% release fraction while the potential error due to heat generation distribution is only [ ] release fraction. This is a reasonable argument that there is no safety concern regarding heat generation distribution, but it may be worth noting that some facets of their standard modeling approach are highly conservative.

For future analyses it is recommended that the heat generation rates applied to the ANSYS thermal model be more clearly documented and more directly tied to their source (the nuclear analysis). The accuracy of the assumed heat generation distribution was not verified in this review. Instead, it was established that the potential error from making the heat generation distribution assumption was small compared to the expected degree of conservatism.

Other thermal model features were investigated. The thermal contact resistance value chosen by GEH to model energy transfer from the B4C to the capsule wall has a long history of use, but it is not based on specific experimental data. The argument that the thermal contact resistance value is appropriate is based on the fact that the pressurization methodology as a whole has been demonstrated to be highly conservative in tests reported in NEDE-33284P-A Revision 2, Appendix C. Confirmatory analyses show it takes a factor of two (or ½) applied to the contact resistance value to make a significant change in the Marathon-Ultra thermal model results.

The helium gap between the cladding and the absorber tube was also investigated. This is another model feature that is conservative rather than precise. It is modeled as a solid material with conduction as the only heat transfer mechanism. In reality, convection and radiation would add additional heat transfer capacity, but under-representing the transfer capacity leads to conservatively higher temperatures in the B4C, which in turn leads to higher internal pressure

and helium release which is conservative in the design analysis.

A confirmatory analysis using the Jens-Lottes (JL) correlation was performed to confirm the thermal model's prediction of the outside absorber tube surface temperature. The FEA model methodology applies a surface conduction coefficient to the outside absorber surface that is based on the JL correlation, which relates total heat flux to outer cladding surface temperature. A comparison between thermal FEA results and temperature estimates based on the JL correlation are listed in Table 2 for the D/S Lattice worst case geometry and Table 3 for the C Lattice nominal geometry. The comparison shows that the FEA model is close to the expected JL correlation value and consistently higher, which is conservative.

Table 1: Boron Carbide Heat Generation Distribution (D/S-Lattice Worst Case)

Distribution	Centerline (°F)	Ring4 OD (°F)	Ring8 OD (°F)
Baseline	[		
Average			]

Table 2: D/S-Lattice Worst Case Dimension Comparison to Jens-Lottes

	Crud Surface (°F)	Tube Surface (°F)
Thermal FEA	[	
Jens-Lottes		]

Table 3: C-Lattice Nominal Dimension Comparison to Jens-Lottes

	Crud Surface (°F)	Tube Surface (°F)
Thermal FEA	[	
Jens-Lottes		]

3.1 Thermal Model RAI Resolution (RAI-1)

The RAI issued to resolve the thermal model issues was in the format of a bulleted four-part question (RAI-01). Each bullet is listed here with a brief summary of the response. All issues raised by this RAI were satisfactorily resolved.

• Explain how the heat generation rates were determined for the thermal model. The B4C material was split into a number of rings, each with a particular heat generation rate. What is the basis for the diameters of the rings and the separate heat generation zones? How do these compare to the Marathon 5-S design, which has a different B4C capsule geometry?

Resolution: The average heat generation was scaled to fit an assumed radial distribution that was originally determined for the Marathon 5-S. The division of the B4C in that case was based on the divisions in the nuclear analysis code. The division of the B4C in the Marathon Ultra

nuclear analysis (4 uniform divisions) did not match the division in the existing thermal model (8 non-uniform divisions) so GEH assumed the distribution would be the same in both cases. The distribution affects the peak and average temperature calculated by the model, but GEH was able to show that assuming a conservative, uniform heat generation distribution would not affect the results enough to raise a safety concern.

• Explain how the convection coefficient that defines heat transfer between the B4C material and the capsule wall was determined. How well does this convection coefficient match experimental data? What physical conditions (such as temperature, diameter, amount of void space, etc.) affect this convection coefficient? Was the same convection value used in the M-5S and ESBWR? Is this convection coefficient intended to represent conduction and radiation heat transfer as well?

Resolution: The convection coefficient represents a thermal contact resistance that is intended to represent all heat transfer mechanisms. This is a constant approximated value that has been used in many design evaluations, including the Marathon, Marathon 5-S, and ESBWR. The justification for this value is that the model results using this value have been demonstrated to be conservative compared to experiments.

• Discuss the representation of the helium gap as a conductive material. With the change in gap size, is it necessary to include convection or radiation for correct heat transfer across the gap?

Resolution: Representing the helium gap as a conductive material is conservative because it neglects the other potential heat transfer mechanisms and thus provides more thermal resistance.

• Explain how the convection heat transfer coefficient between the crud layer and the coolant is calculated. This appears to be based on a Jens-Lottes correlation and modeled as a function of pressure, total heat generation, and exterior surface area. Was this same function used in the M-5S and ESBWR to define the convection coefficient? How well does this function match experimental convection data under similar conditions (temperatures, geometry, flow rates, etc.)?

Resolution: The convection coefficient to the coolant is a direct implementation of the Jens-Lottes correlation in the FEA model and independent calculations agree that it is correctly implemented. The identical method was used in the M-5S and ESBWR. GEH does not have direct comparison data for the Marathon-Ultra, but test data shows the methodology as a whole is conservative.

3.2 Thermal Model Review Conclusions

The review found no FEA modeling errors in the ANSYS thermal model, and confirms that the models were behaving as intended. Confirmatory calculations using the Jens-Lottes correlation show that the ANSYS thermal model predicts the expected exterior temperatures. Some of the model's heat transfer parameters were not confirmable from test data or other

means, but sufficient evidence was presented that the methodology as a whole leads to highly conservative internal pressure estimates. As this is the purpose of the ANSYS thermal model, to calculate internal pressure for comparison against a maximum pressure threshold, this model and methodology are found to be adequate.

The RAI responses provided information to support the conservatism of their methodology and to explain certain features of their model that were not clearly documented. The method of applying heat generation to the thermal model was not transparent, and an alternate evaluation using a conservative uniform distribution was used to show that the potential error in their assumptions was not significant compared to the degree of conservatism in their method as a whole.

Conservatism is a common theme in the ANSYS thermal model and in the RAI responses. The helium gap is treated conservatively as a conduction-only heat transfer path. Neglecting convection and radiation causes less heat to leave the central boron carbide and contributes to higher calculated temperatures. The contact resistance value used between the boron carbide and the capsule wall has been used for many designs, including the ESBWR and the original Marathon design, and its continued use is supported by the conservatism shown in NEDE-33284P-A Revision 2, Appendix C. The crud to coolant heat transfer behavior was similarly justified for its long use and contribution to conservative pressure results.

It should be noted that the model and methodology were demonstrated to be conservative as a whole. The FEA model assumes the maximum heat generation rate with the maximum peaking factor is applied to the entire length of an absorber tube and the only path for heat to leave is through the surfaces that directly contact the coolant. With these extreme assumptions, calculation of the B4C temperature, helium release fraction, and internal pressure should be conservative compared to actual in-reactor behavior. This makes it difficult to determine the contribution of individual model parameters, such as thermal contact resistance, to the overall conservatism of the analysis.

The method of assuming a heat generation profile in the boron carbide based on prior evaluations is a potentially non-conservative feature of the Marathon Ultra ANSYS thermal model. While this approach is found to be acceptable in this case due to the expected degree of overall conservatism, it is recommended that this not be continued in future analyses.

PNNL finds the ANSYS thermal FEA model and analysis methodology as a whole to be conservative, based on a review of the models, confirmatory analyses, the alternate uniform heat generation calculation, and the comparison to pressure test data reported in NEDE-33284P-A Revision 2, Appendix C.

4.0 Handling Load Model

The handling load model investigates the structural load on the handle due to a controlled lift. The load is assumed to be twice the control rod weight (2*g*), which was also used in the Marathon 5-S. The ESBWR lifting load was analyzed at a higher load (3*g*) but it used a substantially different three-dimensional (3D) model and GEH staff explained at the time that 3*g* was known to be excessive. The actual physical lifting load is not well established, but from the

slow speed is expected to be close to 1*g*. There is a small amount of positive buoyancy force in the submerged control blades, so the blades could be lifted with less than 1*g* lifting load applied to the handle. NRC has accepted 2*g* in the past for GEH and other vendors as an adequate representation of the lifting load.

GEH used a two-dimensional (2D) ANSYS FEA model of the handle plates for each of the handle design evaluations. All handle designs except the D Lattice Standard Handle are double bail configurations, comprised of two perpendicular interlocking plates joined by fillet welds. The 3D nature of the double bail designs requires some adjustment for analysis in a 2D model. The geometry of one handle plate is modeled with a thickness that represents the fillet welds instead of the constitutive plates. This method essentially focuses the load on the fillet welds as a conservative and computationally inexpensive simplification and alternative to 3D modeling. PNNL performed a confirmatory analysis of the lifting load on the D Lattice BWR/4 Extended Handle case by creating a 3D model from the 2D geometry of the GEH model. The peak stress intensity predicted in the weld regions of the 3D model was significantly lower than the stress predicted by the 2D model, supporting the conservatism of the GEH analysis method. Table 4 compares the 2D and 3D stress intensity results.

Table 4: Lifting Load Comparison

	Model Type	Model Results (maximum stress intensity)
GEH	2D	[
PNNL	3D	]

There were two initial issues of concern, the choice of temperature (70F) and the particular control rod weights used in the analyses. The necessity of a weld quality factor in the calculations was a third issue, raised during the June conference call/audit. The answer to most of these questions was straightforward. While the temperature was chosen to be 70F, the same ultimate tensile strength is valid up to 200F, and this covers the temperature range of other vendor evaluations. Maximum control rod weights and an appropriate weld quality factor were applied in a set of alternate calculations that showed the lifting stresses still remained below the design limits.

4.1 RAI Resolution (RAI-2)

The RAI issued to resolve the lifting load model issues was in the format of a bulleted two-part question (RAI-02). Each bullet is listed here with a brief summary of the response. All issues raised by this RAI were satisfactorily resolved. GEH also satisfactorily addressed the issue of weld quality factor in their response to the second part of this RAI.

• Discuss the choice of analyzing the lifting load at a material temperature of 70F. Since yield strength and ultimate strength of the handle material decreases with temperature, is this a

conservative temperature assumption?

Resolution: The allowable stress comes from the ASME Boiler and Pressure Vessel Code, and that value remains unchanged up to 200F. See: 2010 ASME Boiler and Pressure Vessel Code, Section II, Part D, "Properties (Customary)", Table U, pp. 486-487, line 46, SA-240, type 316, UNS S31600.

• The 2g lifting loads are based on control rod weights that are less than the maximum control rod weights listed in Table 2-1. Discuss the conservatism of these loads and the choice of control rod weight.

Resolution: GEH performed an alternate set of lifting load calculations assuming a weld quality factor of [ ] and maximum control rod weights from Table 2-1. The results of these more conservative evaluations all remained within the design allowable stress.

4.2 RAI Resolution (RAI-7)

The handle lifting model is also related to RAI-7, which discusses the procedure for employing alternate absorber loads. GEH confirmed that the alternate loading patterns would not exceed the maximum control blade weights listed in Table 2-1, so the alternate lifting load evaluations reported in RAI-2 cover the permissible range of the alternate absorber loads and demonstrate a positive design margin.

4.3 Handling Load Model Conclusions

The handling load ANSYS FEA models were reviewed and found to be free of modeling errors. The choice to model the handles using a 2D method was explored using a 3D confirmatory model and found to be conservative. RAI questions were asked regarding the choice of temperature and the basis of the control rod weight used for the lifting load. The RAI responses explained that the material strength at the evaluated temperature was also correct for the full temperature range of interest. The response to the issue regarding control rod weight included an alternate lifting load study that included the maximum allowable control rod weights and a weld quality factor applied to the results.

The standard lifting load analysis methodology does not include a weld quality factor on the handle stress evaluation. Instead of justifying the lack of a weld quality factor in the calculations, GEH performed alternate lifting load evaluations with a weld quality factor to show that a positive design margin existed for all the handle and lattice designs at the maximum weight listed in Table 2-1 of NEDE-33284P, Supplement 1. When alternate absorber tube loading configurations are considered, the total weight of the control rod may change and necessitate additional lifting load calculations at a new 2*g* lifting load. It is recommended that if such lifting load analyses are necessary, that they include consideration of weld quality. The existing alternate evaluations for the M-Ultra cover control rod weights up to the maximums

listed in Table 2-1, so this will only be an issue if the alternate loading increases the weight beyond those values.

Based on the original and alternate lifting load ANSYS FEA models, PNNL finds that the Marathon Ultra handle designs are sufficient to withstand the handling loads. GEH's established analysis methodology does not include a weld quality factor, but it is recommended that weld quality be considered in future handling load evaluations of welded double-bail handle designs.

5.0 Conclusions

The thermal and handle lifting finite element models of the M-Ultra control rod assembly were reviewed and found to be reasonable and in-line with previous GEH models. The review process involved the sharing of GEH ANSYS input files to facilitate a fast and thorough evaluation of the models. PNNL staff were able to quickly confirm the results reported in the topical report supplement, check the models for errors, and perform confirmatory analyses and parameter variation studies prior to drafting RAI questions. The final RAI responses satisfactorily resolved all open technical questions.

Based on the review of the Marathon Ultra and Marathon-5S it can be concluded that the GEH methodology, inputs, assumptions and design criteria are acceptable and applicable to similar control rod designs. Two recommendations are made for future applications of this methodology. First, the heat generation distribution of the thermal model should be more clearly documented and more directly tied to the nuclear analysis model. Second, the handle lifting load analysis should consider the weld quality in welded double bail designs.

GEH has requested the freedom to alter the absorber material configuration, and these alterations may necessitate a full or partial re-evaluation of the control blade to reflect the changes in composition.

The current evaluation of the Marathon Ultra has considered a maximum control rod weight up to the value reported in Table 2-1 of NEDE-33284P, Supplement 1. If an alternate absorber tube loading configuration exceeds the Table 2-1 weight value it should be re-evaluated for handle lifting load and SCRAM. It is recommended that weld quality be considered in the handle lifting load evaluation, as it was done in the alternate lifting load evaluation performed for RAI-2.

The current evaluation of the Marathon Ultra has only considered 304L stainless steel as the boron carbide capsule material. Changes in capsule material will affect the ANSYS thermal model results and may require adjustments to the analysis methodology to maintain conservatism. [

]. The capsule that encapsulates the B4C is limited to stainless steel since this was the only ANSYS analysis provided.