FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO

BAW-10192P-A, REVISION 0, SUPPLEMENT 1

"BWNT-LOCA: BWNT LOSS-OF-COOLANT ACCIDENT EVALUATION MODEL

FOR ONCE-THROUGH STEAM GENERATOR PLANTS"

## 1.0 INTRODUCTION

Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors," requires, in part, the evaluation of emergency core cooling system (ECCS) performance by analyzing postulated loss-of-coolant accidents (LOCAs) using an acceptable evaluation model (EM). AREVA Inc. (AREVA) maintains an acceptable EM for Babcock and Wilcox (BW) Nuclear Technologies (BWNT) nuclear power plants. The EM is known as BWNT LOCA. BAW-10192P-A, Revision 0, "BWNT LOCA – BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants," is the NRC-approved topical report (TR) that documents the BWNT LOCA EM (Reference 1). This TR was approved by the NRC in a safety evaluation (SE) dated February 18, 1997, and the approved version of the TR, BAW-10192P-A, was published in June 1998.

AREVA submitted Supplement 1 to BAW-10192P-A (hereafter, the TR Supplement) for NRC review by letter dated November 25, 2015 (Reference 2). The supplement provides the technical basis for a correction to the fuel performance modeling used by the EM. The correction accounts for the effects of nuclear fuel thermal conductivity degradation (TCD).

### 1.1 EVALUATION MODEL BACKGROUND

The BWNT-LOCA EM employs a system of computer codes to evaluate ECCS performance for once-through steam generator (OTSG) plants. These include RELAP5/MOD2-B&W (R5/M2-BW) (Reference 3), REFLOD3B (Reference 4), BEACH (Reference 5), and CONTEMPT (Reference 6). The R5/M2-BW program is used to predict system thermal hydraulics, core power generation, and clad temperature response during blowdown. The REFLOD3B program is used to determine the length of the vessel refill period and the core flooding rate during reflood. The BEACH program uses input from REFLOD3B to determine the clad temperature response during the reflood period. The CONTEMPT code is used if containment response calculations are required.

The methodology for developing a model and performing large-break loss-of-coolant accident (LBLOCA) analyses is provided in Volume 1 to BAW-10192P-A. The NRC staff SE documenting the approval basis for the EM is provided in Volume 3, beginning on Page LA-143. Under this EM, fuel thermal-mechanical parameters are treated as input. They are provided by fuel performance analyses using the NRC-approved TACO3 and GDTACO (T3/GDT) computer codes (References 7 and 8).

## 1.2 THERMAL CONDUCTIVITY DEGRADATION (TCD)

As uranium dioxide ($UO_2$) fuel undergoes fission in a nuclear reactor, the fuel lattice structure changes with burnup in a way that tends to reduce the thermal conductivity of the fuel pellets. These changes are caused by irradiation, thermally induced stresses, and the progressive buildup of fission products in fuel pellets. Some nuclear fuel thermal-mechanical performance analysis codes do not fully account for this phenomenon, because the data available prior to the late 1990s were inconclusive regarding the significance of the reduction in thermal conductivity. This phenomenon is known as TCD.

In 2009, the NRC issued Information Notice (IN) 2009-23, “Nuclear Fuel Thermal Conductivity Degradation.” The IN notified licensees of this issue and the possible safety implications (Reference 9). The IN concluded that safety analyses that use fuel performance inputs from models that do not accurately account for TCD as a function of burnup may be less conservative than previously understood.

Based on an ongoing NRC staff review of the impact of TCD on nuclear power plant safety analyses, the NRC issued Supplement 1 to IN 2009-23 in 2012 (Reference 10). The IN supplement discussed that the NRC had issued letters to each major fuel vendor, requesting each to evaluate the effects that compensating for TCD would have on plant safety analysis. Such a request was issued to AREVA by letter dated March 23, 2012 (Reference 11).

Also based on its ongoing review, the NRC staff determined that adjusting fuel performance parameters to account for TCD accurately could cause the results of realistic ECCS evaluation models to differ significantly when compared to results obtained using parameters that do not account for TCD. The NRC released IN 2011-21, “Realistic Emergency Core Cooling System Evaluation Model Effects Resulting from Nuclear Fuel Thermal Conductivity Degradation,” discussing the information gathered by the NRC staff that led to this determination (Reference 12).

## 1.3 TCD EFFECT ON BWNT LOCA

The impact of the TCD effect in a LOCA transient is primarily an increase in the fuel initial stored energy, represented by the volume-average fuel temperature (VAFT) in an ECCS evaluation. This increase is a direct consequence of the reduction in fuel thermal conductivity with burnup. The TCD effect is expected to be more prominent in hypothetical LBLOCA scenarios, where the peak cladding temperature (PCT) typically occurs within several minutes of event initiation. As the break size is reduced, the LOCA event progression is extended, and the cumulative impact of decay heat tends to have a greater governing influence on the event than the fuel initial stored energy. As a result, for small-break loss-of-coolant accidents (SBLOCAs), the stored energy is largely removed prior to core uncovery and its contribution to the outcome tends to be minor.[1]

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[1] In addition, the use of a conservative decay heat approximation, such as 1.2 times the ANS/ANSI 5.1-1971 decay heat standard as required per 10 CFR 50 Appendix K, Part I, “Required and Acceptable Features of ECCS Evaluation Models,” results in an overestimation of this heat source that would be expected, at least partially, to offset an underestimation of the initial stored energy of the fuel. For this reason, it was generally believed that realistic ECCS EMs would be more susceptible to non-conservative effects resulting from neglecting TCD than Appendix K-conformant methods, such as BWNT LOCA.

### 1.3.1 Initial Assessment

After the publication of IN 2009-23, AREVA assessed the impact of TCD in its safety analysis methods. In response to Reference 11, AREVA stated that additional detail about this assessment would be discussed with the NRC staff during the 2012 AREVA Fuel Performance Update Meeting (Reference 13). At that meeting, AREVA provided results of several studies relevant to B&W plants (Reference 14). These studies were based on comparisons among T3/GDT, COPERNIC2 (Reference 15), and a newer fuel performance code, GALILEO (Reference 16), which was under development at that time. Based on these initial studies, AREVA considered that the TCD effects in T3/GDT were adequately compensated through a combination of conservative initialization practices and uncertainty applications. AREVA also estimated that significant impacts on PCTs predicted using the BWNT LOCA EM would not be expected.

### 1.3.2 2014 Reassessment

Following the initial assessment described above, AREVA continued developing GALILEO (Reference 17). This model development effort included code-to-code comparisons between the newer, developmental models contained in GALILEO and those contained in legacy models such as RODEX2 (Reference 18) and T3/GDT.[2] As a result of this inter-comparison, AREVA determined that the LOCA initialization for T3/GDT, when compared to a more complete version of GALILEO, produced fuel temperatures that were significantly lower. This under-prediction reduces stored energy in the fuel and leads to non-conservative effects in the ECCS evaluation.

Based on the 2014 reassessment effort, AREVA determined that PCTs predicted using the BWNT LOCA EM and initialized with fuel stored energy from T3/GDT, were significantly under-predicted. AREVA reported this condition under 10 CFR Part 21, "Reporting of Defects and Non-Compliances" (Reference 19). Following submittal of the Part 21 Report, each NRC licensee affected by the defect submitted a report under the reporting requirements contained in 10 CFR 50.46(a)(3)(ii) (References 20 - 23). The reports all confirmed that the affected licensees had implemented linear heat rate penalties as a corrective action to ensure that plant operation remained safe.

## 1.4 PURPOSE OF SUPPLEMENT

Based on the NRC staff review of References 20 - 23, AREVA opted to develop the TR Supplement, which corrects the fuel stored energy for TCD (References 24 - 27). Upon NRC review and approval of the TR Supplement, the affected NRC licensees will be able to use the methods described therein to perform limited re-analyses of ECCS performance. These re-analyses will enable the affected licensees to remove the linear heat rate penalties that have been applied since the discovery of the issue.

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[2] The new information introduced by the GALILEO development effort revealed that the 2009 vendor assessment may have been too limited in scope to identify the T3/GDT inadequacies, and as a result, the NRC staff review of the TCD correction documented in the TR Supplement ensured that a broader set of experimental and code-to-code comparisons support the adequacy of the present TCD augmentation.

## 2.0 REGULATORY EVALUATION

The BWNT LOCA EM was developed in accordance with the regulatory requirements established in 10 CFR 50.46. The EM conforms to the required and acceptable features of ECCS EMs set forth in Appendix K to 10 CFR Part 50, consistent with the passage in 10 CFR 50.46(a)(1)(ii), which states, "Alternatively, an evaluation model may be developed in conformance with the required and acceptable features of appendix K ECCS Evaluation Models."

The NRC staff reviewed BAW 10192PA-R0-S1P and supporting documentation to determine (1) whether the EM changes are conformant to the requirements set forth in Appendix K to 10 CFR Part 50, specifically, those contained in Paragraph I.A.1, "The Initial Stored Energy in the Fuel," and (2) whether the EM, as modified to account for TCD, remains more generally in conformance with the remaining required and acceptable features of ECCS EMs contained in Appendix K to 10 CFR Part 50, and the requirements for ECCS performance contained in 10 CFR 50.46.

## 3.0 TECHNICAL EVALUATION

The TR Supplement presents an approach to capture the effect of TCD in the BWNT LOCA EM. The VAFTs calculated by T3/GDT are augmented by way of a bias factor. The bias factor is treated as an additional uncertainty that is applied to the T3/GDT VAFTs. Calculations from the more recent fuel performance code, COPERNIC2, which includes models to account for TCD, provide the basis for the TCD correction.

The methodology adjustments were not limited just to the VAFTs supplied by T3/GDT, however. Because of differences in the way the fuel performance codes (i.e., T3/GDT and COPERNIC2) are initialized to supply input to the suite of LOCA analysis codes (i.e., R5/M2-BW, BEACH), some modifications to the fuel performance code initiation process were necessary to incorporate the TCD augmentation. Similarly, modifications[3] to the fuel pin and heat structure models within the LOCA codes were necessary to apply the TCD-modified fuel performance input supplied by the fuel performance codes.

The NRC staff conducted an audit, following Office of Nuclear Reactor Regulation Office Instruction LIC-111, "Regulatory Audits," to identify additional information required to complete the review (Reference 28). The audit (Reference 29) was conducted on April 25 and 26, 2016, in Rockville, Maryland. The focus of the audit was on the approach, implementation and qualification of the adjustments to confirm that AREVA adequately models TCD as a function of burnup. During the audit, the NRC staff and Brookhaven National Laboratory consultants identified additional information that would be required to support a regulatory determination regarding the acceptability of the TR Supplement.

These information needs were documented in a request for additional information (RAI) letter and formally transmitted to AREVA (Reference 30). The RAI letter consisted of a set of 21 RAI questions. Pertinent information from the responses to the RAI questions (Reference 31) has been incorporated into this SE. Several corrections to the TR Supplement, mostly a result of responses to the NRC questions, were also provided in the markup section at the end of the response to the RAI questions.

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[3] Such modifications were made to parameters and coefficients that are supplied as user input, and not necessarily to the model correlations or their implementation within the computer codes.

In its review, the NRC staff considered all of the adjustments to the BWNT LOCA analytic process described above. This technical evaluation describes the review effort, and is organized as follows. First, an overview of all the modifications made to incorporate the effects of TCD is provided. Second, differences in steady-state fuel performance code initialization are discussed and evaluated. Third, the adjustments to the T3/GDT VAFTs are reviewed, including their developmental basis and qualification for implementation. Fourth, modifications to the approach for modeling the fuel pins within the LOCA codes is discussed and evaluated. Finally, the application of the TCD-adjusted fuel parameters in the overall EM is evaluated by considering some demonstration analyses provided by AREVA.

## 3.1 SUMMARY OF ANALYTIC PROCESS AND TCD-BASED ADJUSTMENTS

The analytic process is summarized below, with focus on developing an appropriate initial stored energy for running BWNT LOCA.

Currently, the approved method for initialization of the fuel pin models in BWNT LOCA for LBLOCA analysis is summarized in Section 4.3.2.3 of Revision 0 to BAW-10192P-A (Reference 1) as follows:

> The initial temperature distribution in the fuel is determined by an NRC-approved steady-state fuel pin model (at present TACO3…). The input is consistent with the time in life, or bounds the time-in-life values for the case or range of burnup values that is under investigation in the LOCA study. The initial internal fuel pin pressure, radial fuel power shape, internal pin gas composition, and initial fuel pin oxide thicknesses are specified by the steady-state fuel code as well.
>
> RELAP5/MOD2-B&W runs are initialized by using the initial average fuel temperature [i.e., VAFT] from the approved steady-state fuel code. Calculated results and input parameters from the fuel pin code (such as cladding and fuel dimensions, surface roughness, radial power shape within the fuel, gas composition, gas pressure, fuel-clad contact pressure, plenum volumes, etc.) are input. The average fuel temperatures will be adjusted using a pin gap conductance multiplier to match within 20 F, those predicted by the fuel thermal code.

The TR Supplement presents an update to the existing LOCA initialization process described above, encompassing changes in the EM methodology. The changes in the EM methodology include the aforementioned changes in fuel performance code input handling within the code system. While it is understood that the changes apply equally to fuel performance code inputs to both R5/M2-BW and BEACH, the SE discusses R5/M2-BW primarily. The input transfer and code adjustments to BEACH are identical to R5/M2-BW. The changes include:[4]

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[4] Nomenclature will be introduced for the VAFT terms and the bias factor in Section 3.3. The nomenclature is not used in this bullet list to preserve brevity.

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
    - [ ]
    - [ ]
    - [ ]

The response to RAI 1 provides a more detailed description of the analytic process, including an expanded LOCA EM flow chart (see Figure 1). The flow chart highlights portions of the LOCA analysis that are changed as a result of modifications to the LOCA EM to incorporate TCD effects. As illustrated in Figure 1, the modified LOCA analysis documented in the TR Supplement relates only to the preparation of inputs to the R5/M2-BW code. There is no change to the source code of the five computer code applications described in BAW-10192P-A, Revision 0 (Reference 1). The function of these five codes and the interfaces among them are summarized in the response to RAI 1.

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**Figure 1. LBLOCA Evaluation Model Flow Map (Reference 31)**

## 3.2 STEADY-STATE INITIALIZATION FOR FUEL PERFORMANCE CODE

The primary purpose of fuel performance codes like T3/GDT is to "provide predictions of the thermal and mechanical performance of… fuel rods experiencing variable power histories up to a particular burnup level" (Reference 7, Page vii). This purpose is general, in contrast to the more limited purpose of determining fuel pin thermal conditions for the purpose of initiating an analysis of a hypothetical LOCA. Recognizing this contrast, fuel performance models typically have a specific initialization process in order to generate the initial conditions needed to run the ECCS evaluation.

Noting the above, COPERNIC2 and T3/GDT employ slightly different methods to initialize the fuel rods to reach the time-in-life (TIL) for LOCA analysis and to provide a best-estimate value of VAFT for the preparation of 95/95 VAFT inputs to the LOCA transient calculation. A comparison of the currently approved methods for both codes is provided in Table 1, below.

| Condition | COPERNIC2 | TACO3/GDTACO |
|---|---|---|
| Power History | **[ ]** | **[ ]** |
| TIL | **[ ]** | **[ ]** |
| Power Level Hold Time | **[ ]** | **[ ]** |
| Treatment of Oxide | **[ ]** | **[ ]** |

**Table 1. Comparison of COPERNIC2 and T3/GDT LOCA Initialization.**

As described in Section 3.1, the T3/GDT initialization process in the TR Supplement is modified slightly relative to the current procedure shown in Table 1 in order to accommodate the TCD adjustments. **[ ]**. These changes allow a consistent basis for the TCD bias uncertainty increase, which is applied based on comparisons to the COPERNIC2 code.

The NRC staff review of the modifications to the T3/GDT initialization process focused on two modifications to the initialization process, and the **[ ]**.

The **[ ]** modeling option was the subject of RAI 8. AREVA responded that its calculations with T3/GDT indicate that allowing **[ ]**. The response to RAI 8 provides additional **[**

**]**. The response to RAI 8 further indicates that the effects of **[** **]** applied to the best estimate VAFT results to achieve the 95/95 one-sided upper tolerance limit temperature (Section 5 of Reference 15).

In determining the appropriate bias function based on COPERNIC2, AREVA performed a set of comparative analyses with COPERNIC2 and T3/GDT that used a simplified initialization process that did not include a **[** **]**. In the response to RAI 7, AREVA provides evidence indicating that this method for determining a bias function for penalizing the VAFT calculated by T3/GDT is appropriate. Specifically, AREVA stated that the validation cases presented in the TR Supplement demonstrate that the penalized VAFT from T3/GDT is always greater than or equal to the uncertainty-adjusted 95/95 upper tolerance limit VAFT from a COPERNIC2 case with the **[** **]** included. The validation cases and results of the case-to-case comparisons are discussed and summarized in Section 3.2.1 and Table 3-3 of the TR Supplement (Reference 2), respectively. Since the validation demonstrates that the chosen biasing method results in T3/GDT VAFT values that are conservative relative to COPERNIC2 values that are initialized using the approved initialization process, the NRC staff determined that the simplified approach that eliminates the **[** **]** was acceptable for use in determining the TCD bias function.

Based on the considerations discussed in the preceding paragraphs, the NRC staff concluded that the modified initialization process is acceptable. Namely, the response to RAI 8 indicated that the **[** **]**. In addition, the response to RAI 7 indicates that the T3/GDT penalized VAFTs are conservative relative to COPERNIC2 values that are initialized using an approved initialization process.

## 3.3 APPLICATION OF TCD BIAS FACTOR

The TR supplement presents an approach to augment the VAFTs calculated by T3/GDT to account for the TCD effect. The adjustment to the VAFTs is by way of a bias factor developed as an uncertainty to the calculation of fuel temperatures. This bias factor is determined by comparing fuel temperatures calculated by COPERNIC2, which accounts for TCD effects, and T3/GDT, which do not account for TCD effects.

### 3.3.1 Summary of Bias

A simple solution for the temperature of a solid fuel pellet is used to illustrate the rationale behind the formulation of the bias factor presented in the TR Supplement. It is noted that the temperature difference across a solid fuel pellet with uniform power density and constant thermal conductivity is fixed by the LHR. This temperature difference is inversely proportional to the thermal conductivity of the fuel and independent of the pellet outer radius. Furthermore, the VAFT is given by

$$VAFT = \frac{(FCT + FST)}{2}, \qquad (1)$$

where FCT is the fuel centerline temperature and FST is the fuel pellet outer surface temperature. Building on the above expression, consider the 95/95 upper tolerance limit VAFT

as a sum of the best-estimate VAFT ($VAFT^{BE}$) and its associated uncertainty represented by a combination of the uncertainties for the fuel centerline temperature and the fuel surface temperature.

In COPERNIC2, the uncertainty is represented as a **[ ]**, as follows:[5]

**[ ]** (2)

By contrast, T3/GDT uses **[ ]**:

**[ ]** (3)

The approach presented in the TR Supplement includes the TCD effect as an uncertainty in the VAFT calculated by T3/GDT to account for the fact that these codes do not incorporate models for TCD. In the TR Supplement, the VAFT calculated by T3/GDT is taken as the best-estimate VAFT ($VAFT^{BE}$). Meanwhile, the 95/95 upper tolerance limit VAFT ($VAFT^{\frac{95}{95}}$), corrected for the TCD effect, is the sum of $VAFT^{BE}$ and an uncertainty term. The uncertainty term has **[ ]**. The 95/95 VAFT thus takes the form,

**[ ]** (4)

The TR Supplement further assumes the **[ ],** taking a form similar to the T3/GDT uncertainty,

**[ ]** (5)

Conceptually, using the solid fuel pellet as a model, the bias part of the uncertainty term for the $VAFT^{\frac{95}{95}}$ then represents the TCD effect on the fuel centerline temperature and the fuel pellet surface temperature. In the TR Supplement the bias is formulated to be a function of the **[ ]**,

**[ ]** (6)

After accounting for the TCD effect, the adjusted $VAFT^{\frac{95}{95}}$ based on the T3/GDT output assumes the form,

**[ ]** (7)

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[5] The default temperature units for COPERNIC2 are °C; however, TACO3, GDTACO, and BWNT LOCA use °F.

For T3/GDT, **[ ]**. Adding this inequality to the above equation and substituting the right hand side of Equation (2) for $VAFT_{COPERNIC2}^{\frac{95}{95}}$ yields

**[ ]** (8)

AREVA solves for this inequality to obtain the basis for the burnup-dependent bias used to establish the TCD correction. It is

**[ ]** (9)

The inequality above provides a means by which to establish the bias based on comparisons between COPERNIC2 and T3/GDT. The TR Supplement provides the results of such comparisons, and the values of $\boldsymbol{f}(\boldsymbol{BU})$ for $UO_2$ and gadolinia fuel are given in Figures 3-6 (Table 3-1) and 3-8 (Table 3-2) of the TR Supplement, respectively. Based on these figures, a simplified diagram depicting the uranium and gadolinia bias functions is shown below, in Figure 2. The response to RAI 9 notes that, since the native unit of temperature in T3/GDT is °F, the TCD bias is developed in that unit as well.

[ ]

**Figure 2. The *f(BU)* TCD bias functions for gadolinia (top line) and uranium dioxide (bottom line) fuel.**

### 3.3.2 Technical Basis and NRC Staff Review

The adjustment described above is based on the presumption that COPERNIC2 includes models and correlations that adequately model the TCD phenomenon. The COPERNIC2 code is approved for use by the NRC, and the NRC staff SE approving it discusses the review of COPERNIC2 fuel thermal conductivity models against high-burnup data, which supported favorable conclusions regarding the adequacy of the models with regard to burnup-dependent TCD.[6] Thus, the NRC staff accepted the presumption that COPERNIC2 can adequately model TCD.

AREVA further demonstrated the adequacy of the generic bias function by comparing to **[ ]** experimental fuel rods that achieved high burnup conditions. These comparisons are discussed in Section 3.2.2 of the TR Supplement.

The 95/95 VAFT calculated by COPERNIC2 is established in Equation (2). In Section 3.2.2 of the TR Supplement, a comparison of temperatures between calculated and measured data from the high burnup test rods is used to validate the generic TCD bias functions. The following equation, however, which is shown as Equation 7 on Page 3-12 of the TR Supplement does not actually represent a statistical determination of the 95/95 centerline temperature; rather it is a surrogate that facilitates comparison to the high-burnup, instrumented test rods. AREVA notes that "**[**

**]**"

**]** (10)

The equality shown in the equation above is at best a postulation. However it can be inferred from Equation (8), above, and the discussion in the first paragraph on Page 4-5 of the TR Supplement, that if the COPERNIC2 95/95 uncertainty of **[ ]** °F is subtracted from the right hand side of Equation (10), above, the resulting temperature should then represent a best-estimate prediction of centerline temperature that accounts for TCD. That is,

**[ ]** (11)

Using the above formulation as the predicted FCT, AREVA shows in response to RAI 20 that the predicted-minus-measured FCT differences that bound 95 percent of the data with a 95 percent confidence level, assuming a normal distribution, is **[ ]** °F. The response to RAI 20 notes that according to the shape of the histogram the data is not a normal distribution. The response then evaluates the 95/95 limit using order statistics. According to order statistics, with 95 percent confidence at least 95 percent of the population of (measured - predicted) values will be less than **[ ]** °F. Therefore, the value of **[ ]** °F calculated under the assumption of normally distributed data is conservative. Since both methods estimated a temperature bias that is less than **[ ]** °F, this exercise shows that the generic bias functions

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[6] The basis for this determination is provided in the NRC staff SE for Revision 0, in Section 2.1. This SE is included in Reference 15.

have adequately penalized the T3/GDT fuel temperature predictions to account for the TCD effect.

The scatter of data in Figure 3-10 of the TR Supplement suggests that, despite that the T3/GDT measured-to-predicted ratios to **[** **]**. In response to RAI 4, AREVA notes that the observed trends with **[** **]**. The magnitude of degradation in thermal conductivity is a combined effect of the burnup and the fuel temperature (or LHR). As shown in Figure 3-7 of the TR Supplement, the TCD effect is more pronounced at lower fuel temperatures/LHR than at higher temperatures/LHR. The TCD bias functions are formulated as an **[** **]** for the VAFT and they are designed to conservatively bound the influence of fuel temperature/LHR at a given burnup. The response to RAI 4 notes that for **[** **]**. This causes the generic bias functions to be very conservative at low LHR and progressively become more accurate as the LHR increases, resulting in the observed trend with the LHR in Figure 3-10 of the TR Supplement.

Despite that the data supporting Figure 3-10 is limited to linear heat rates below **[** **]**, the response to RAI 4 also notes that "COPERNIC2 has been validated to a much broader database of measured data than those presented in Figure 3-10" (Page 4-2, Reference 31). Thus, according to AREVA, the code-to-code comparisons, i.e., T3/GDT to COPERNIC2, supplement the qualification against experimental data. Shown in Table 3-3 of the TR Supplement are comparisons of COPERNIC2 95/95 VAFT predictions to biased predictions from TACO3 to linear heat rates as high as **[** **]**. Furthermore, AREVA augmented its validation case set in response to RAI 6, which is discussed further below. In view of the above, the NRC staff acknowledged that the LHR-dependent comparisons shown in Figure 3-10 may be somewhat inconclusive in terms of showing that the TCD bias functions are adequate at higher LHR values. However, because the TCD bias functions are **[** **]**, and because the functions are also qualified using COPERNIC2 code-to-code comparisons including higher linear heat rate cases, the NRC staff determined that the functions were adequately qualified despite the data trends shown in Figure 3-10. The NRC staff also considered the fact that COPERNIC2 is NRC-approved without limitation on linear heat rate in reaching this determination.

In RAI 2, the NRC staff requested further information concerning the characteristics of the fuel performance code cases that were used to determine the TCD bias function that is applied to the T3/GDT initialization parameters (i.e., initialization parameters that are supplied to R5/M2-BW). In response, AREVA provided a description for each case shown in Figures 3-1 through 3-6 and Figure 3-8 in the TR Supplement, including axial power shape and rod power history. Each case is represented in the figures by several series of data points. Each series corresponds to one of the **[** **]** used by the steady-state fuel performance codes to model a fuel rod. In some cases the series ended before the end of the power history because the rod pressure limit of **[** **]** was exceeded. The response to RAI 2 notes that the "LHR limit" presented in Figures 3-1 through 3-5 of the TR Supplement is to represent a typical example of the peak LHR used in the LBLOCA PCT evaluation.

The purpose of showing the LHR limit on the figures is to demonstrate that the range of nodal burnup and nodal LHR analyzed in the suite of cases used to determine the generic TCD bias functions adequately bounds the expected range of application. It is noted that the suite of cases included the LOCA initialization axial power with a peak-to-average axial power of **[ ]**.

The descriptions of the cases provided in the response to RAI 2 indicate that the case set includes: (1) fuel rods operated in typical, in-reactor conditions, (2) fuel rods affected by severely skewed power shapes, (3) fuel rods operated at high LHR values representative of LOCA analysis input values, and (4) fuel rods given power histories to permit obtaining high burnup values. The variety in the cases supports the conclusion that the range of burnup and nodal LHR values bound the expected range of application for the generic TCD bias function.

Reviewing the TR Supplement, it is apparent that the LHR limits shown on Figures 3-1 through 3-6 are different from, and lower than, those shown in Figure 5-18. The response to RAI 10 provides discussion to clarify the differences between these figures. First, Figures 3-1, 3-2, and 3-5 of the TR Supplement show the thermal LHR, while the nuclear source LHR is shown in Figure 5-18. The total power produced in the core is the nuclear source. The LOCA peaking is defined in terms of the nuclear source peaking and rod average burnup, and they are the information conveyed in Figure 5-18 of the TR Supplement. The thermal power is the energy deposited in the fuel and is lower than the nuclear source power because part of that energy goes to direct energy deposition in the moderator. The energy deposition factor (EDF) is defined as the ratio of the thermal source LHR to the nuclear source LHR. The response to RAI 10 also notes that the hot spot location can be slightly lower than the peak burnup if the power shape is highly skewed towards the top or bottom of the rod. Using the x-y coordinates of the slope transition point on the $UO_2$ curve in Figure 5-18 as an example, the response to RAI 10 illustrates the mapping of that point onto the nodal thermal LHR versus nodal burnup (local) coordinate system represented in Figure 3-1. The illustration demonstrates the equivalency of the two coordinate systems represented in Figures 3-1 and 5-18 of the TR Supplement, respectively. The mapping made use of typically assumed values for EDF (0.973) and maximum local burnup (15 – 20 percent greater than the rod average burnup). Since AREVA established that the LHR limits depicted in Figure 5-18 are the same as those shown in Chapter 3, the NRC staff determined that the issue contained in RAI 10 was resolved.

In response to RAI 6.a AREVA outlines the three components that are required by R5/M2-BW to reconstruct the radial temperature profile in the fuel pellet:

1) A value for VAFT that is adequately adjusted for the TCD effect – Section 3.2.1 and Table 3-3 of the TR Supplement present code-to-code comparison cases between T3/GDT and COPERNIC2 demonstrating that the TCD bias functions conservatively meet the objective. The response to RAI 6.a provides 10 more code-to-code comparison cases (results summarized in Table 6-1 of the response) covering additional gadolinia concentrations and a larger range of linear heat rate for each fuel type. In all cases the penalized T3/GDT VAFT is greater than the 95/95 VAFT from COPERNIC2, demonstrating that the VAFT is adequately adjusted for the TCD effect.

2) An accurate model of the radial power distribution in the fuel pellet – This phenomenon is not affected by the TCD and the predicted power profiles from T3/GDT remain applicable (see also discussion in Section 3.4 and Table 3-5 of the TR Supplement).

3) Appropriate thermal conductivity for the burnup and temperature conditions of the fuel pellet – Section 4.2.1 of the TR Supplement discusses modifications to the fuel thermal conductivity modeling in R5/M2-BW to initialize the LOCA analyses.

The results of implementing the above three components in the TR Supplement to initialize fuel pellet temperature for LOCA analyses are illustrated in Figures 4-4 and 4-5. The response to RAI 16 notes that some of the curves in the two figures were mislabeled, and revised figures are included as part of the response. AREVA indicated that the revised figures would be included in the approved version of the TR. In addition, the response to RAI 17 clarifies a statement on Page 4-9 of the TR Supplement, referring to the most obvious shift at the fuel and clad interface as shown in Figure 4-5. The shift that is alluded to in the text of the TR Supplement is a shift in radius, not temperature, as the interface between the fuel and cladding is shown at different radii for different codes. This clarification is included in a revised Page 4-9 attached to the responses to RAI 17 and will be included in the approved version of the TR.

The response to RAI 6.b illustrates the process of transforming the VAFT from T3/GDT to R5/M2-BW heat structure initial temperatures. It includes a description of an important step not mentioned explicitly in the TR Supplement, that of the use of a multiplier at axial levels other than the hot spot (i.e., along the entire fuel rod) to get the 95/95 T3/GDT VAFT values, which account for the VAFT uncertainty and the TCD bias. Details of the process discussed in the response to RAI 6.b are significant for the implementation of the modified LOCA methodology, such as the use of different temperature scales in different parts of the process to transform the VAFT. Below is a summary of the process for combining the generic TCD bias factor with the steady-state fuel performance code 95/95 VAFT uncertainty to initialize the hot pin VAFT that produces conservative fuel stored energy input for TIL LOCA analyses:

1) **[ ]**

2) **[ ]**

3) **[ ]**

4) **[ ]**

5) **[ ]**

6) **[ ]**

7) **[ ]**

8) **[ ]**

The eight step process is denoted the multiplicative ratio approach. The response to RAI 6 b demonstrates the validity of the multiplicative ratio approach to get the TCD-biased 95 95 VAFT

for the entire rod, even for the lower power regions of the rod. This is by way of comparing the COPERNIC2 95/95 VAFT and the TCD-adjusted 95/95 VAFT calculated by the multiplicative ratio approach. The comparison shown in Figure 6-3 of the response to RAI 6 validates the applicability of the multiplicative ratio approach to determine the 95/95 VAFT over the entire hot pin when the generic TCD bias method is used.

In the response to RAI 6.b AREVA notes that in the example case used to illustrate the 8-step multiplicative ratio approach, the local burnup for several axial nodes immediately above the hot spot (i.e., the node with the peak VAFT) is higher than the nodal burnup for the hot spot. As reflected above in Step 2 of the 8-step process, in order to incorporate conservatism in the initialization of VAFT for LOCA analyses, AREVA stated that future generic TCD bias licensing cases will use the maximum burnup on the rod (i.e., in lieu of the nodal burnup at the peak fuel temperature) to establish the additional VAFT increases to account for the TCD effect. Consideration of the maximum burnup on the rod ensures that the TCD augmentation is bounding of the burnup characteristics for the entire rod, rather than just the peak node.

The applicability limits for the TCD bias functions provided in Table 3-4 of the TR show a range of parameter values, such as radial dimensions of a fuel rod and initial pellet density. RAI 3 requested AREVA to compare the limits in Table 3-4 against the applicability range for the computer codes (i.e., COPERNIC2, T3/GDT) and the experimental data used in the development of the TCD bias functions. In response to RAI 3, AREVA notes that **[**

**]**. AREVA further points out that the generic TCD bias functions developed in the TR Supplement are based on the current Mark-BHTP™ fuel rod design. Therefore, the applicability limits for the generic bias functions will be based on the nominal design parameters for the current Mark-BHTP™ fuel rod design. AREVA provides a new table in the response to RAI 3 (Table 3-1 in the response) listing the recommended applicability limits for the generic TCD bias functions. A comparison of the revised limits in that table with the T3/GDT and COPERNIC2 range of applicability (Table 3-2 of response to RAI 3) indicates that the range of applicability for the generic TCD bias functions is bounded by the range of applicability for the fuel performance codes. Table 3-3 in the response to RAI 3 also provides the key design parameters of the experimental fuel rods used in the validation of the generic TCD bias functions. Except for the fuel enrichment (**[** **]**) in one of the experimental rods, all other key design parameters are within the range of applicability for the fuel performance codes. AREVA notes in the response to RAI 3 that the generic TCD bias functions, as presented in the TR Supplement, were calculated for use at the hot spot of the current Mark-BHTP™ fuel rod design. Thus, a more limited range of applicability for the generic TCD bias functions will be implemented in the modified LOCA methodology. This will be reflected in the approved version of the TR in which AREVA will replace Table 3-4 in the TR Supplement with Table 3-1 in the response to RAI 3.

In response to RAI 5, AREVA notes that currently all fuel at domestic, operating B&W plants is the Mark-BHTP™ fuel rod design. The fuel rod characteristics shown in Table 5-1 of the response to RAI 5 are consistent with those in Table 3-1 of the response to RAI 3. The NRC staff determined that the generic TCD bias functions, as presented in the TR Supplement, are applicable to the current fuel design in the B&W plants.

Based on the review described above, the NRC staff determined that the generic TCD bias functions are acceptable for providing VAFT input to the BWNT LOCA ECCS EM. When compared to experimental data, application of the bias functions were shown to produce bounding fuel temperature estimates for the range of burnups evaluated in the LOCA analyses.

Although application of the bias functions is based **[** **]**, the functions were still shown, via code-to-code comparison, to produce a bounding fuel temperature augmentation at higher linear heat rates.[7] In addition, the use of code-to-code comparisons, both those used to define the bias functions and those used to qualify them, indicate that the adjustments are bounding of operational characteristics including those anticipated in normal operation and those used when initializing analysis of the postulated LOCA event. Meanwhile, AREVA's additional applicability constraints on the generic bias functions ensure that they will be applied in conditions consistent with the bias functions' definitions and qualifications.

3.3.3 Steady-State Fuel Temperature Initialization Changes

Section 4 of the TR Supplement discusses LOCA EM changes to account for TCD. The revised LBLOCA EM continues to use fuel pin input from T3/GDT to set the hot, expanded fuel pin initial conditions and the 95/95 core stored energy at the onset of the LOCA (represented in the LOCA initialization by the 95/95 VAFT). Beginning-of-life (BOL) methods remain unchanged because the effects of TCD are minimal as the degradation is not significant. For TIL analysis at middle-of-life (MOL) and end-of-life (EOL) the TCD effect is reflected in the calculation of the 95/95 VAFT, obtained by applying to the BE VAFT an uncertainty factor and an additive adjustment to account for the TCD effect (a burnup-dependent bias factor). In the LOCA initialization the generic TCD bias functions become non-trivial above 1 GWd/mtU (nodal burnup) for both $UO_2$ and gadolinia fuels. The generic TCD bias function for the gadolinia fuel (Table 4-2 of the TR Supplement) is shown to be more limiting than the $UO_2$ fuel (Table 4-1 of the TR Supplement).

The R5/M2-BW (Reference 3) core model for LOCA analyses has two coolant channels for the fuel assemblies, an average channel and a hot channel. The hot assembly is located in the hot channel. The $UO_2$ fuel rods in the hot assembly are modeled by two heat structures, a hot pin, and a hot bundle that represents the balance of $UO_2$ fuel rods in the hot assembly. The gadolinia rods are modeled as separate hot pins in the hot channel. Thus the hot bundle shares the same coolant channel with all the hot pins. The response to RAI 6.c provides a description of the process to determine the 95/95 VAFT for the hot bundle; the process is similar to that outlined above, in Section 3.3.2, for the hot pin.

The bundle uncertainty factor is different from the hot pin uncertainty factor. It is **[** **]** of the BE VAFT (in degrees Celsius (°C)) from T3/GDT for BOL and TIL respectively. The uncertainty of **[** **]** (discussed in Section 4.1 of the TR Supplement) **[** **]**. The techniques employed to determine the new hot bundle uncertainty using the COPERNIC2 results are the same ones (described in Section 5 of Reference 3, beginning on Page 5-494) that were used in the past to calculate the bundle uncertainty using T3/GDT results. Thus, when performing BOL analyses, a **[** **]** (i.e., typically the next burnup step) and above. If the hot bundle **[** **]**.

---

[7] Although not explicitly discussed above, the response to RAI 6.a notes that the COPERNIC2 database includes high burnup, high linear heat rate data.

Figures 4-1 and 4-2 of the TR Supplement provide an expanded view of Figures 3-6 (for $UO_2$ fuel) and 3-8 (for gadolinia fuel) respectively in the low burnup region of the plots. The data shown in Figures 4-1 and 4-2 suggest that no TCD bias or adjustment for code to code differences is needed for local burnups less than 1 GWd/mtU, although the lowest burnup data points are 4 GWd/mtU and 2 GWd/mtU, respectively. Even so, a straight line that originates from 1 GWd/mtU and intersects the TCD bias function at 10 GWd/mtU is shown to envelop all TCD bias data displayed in Figures 4-1 and 4-2. Figure 4-3 of the TR Supplement shows that for a representative $UO_2$ VAFT between rod average burnup of 0 and roughly 20 GWd/mtU, the BOL VAFT is limiting. VAFT decreases initially from BOL with burnup because of gap closure and then increases due to the TCD effect. If LOCA analyses are needed for burnups between **[** **]**. The 95/95 VAFT at the hot spot is determined at **[** **]** respectively. A linear interpolation based on burnup is used to determine the 95/95 VAFT for the hot spot at the desired local burnup. The multiplicative ratio approach is then used to determine the corresponding VAFT at axial locations away from the hot spot. The response to RAI 15 provides additional information to reinforce the discussions in Section 4.1 of the TR Supplement and summarize modifications to the previously approved methodology to initialize VAFT for the hot pin and the hot bundle. The differences between the modified methodology and the previously approved methodology are:

1) **[** ]

2) **[** **]**

3) **[** **]**

4) **[** **]**

5) **[** **]**

The NRC staff reviewed these changes and determined that, since they represent appropriate modifications to accommodate the new TCD augmentations, and they provide a reasonable transition from unbiased (i.e., low-burnup) to biased VAFT inputs, the changes are acceptable.

3.4 <u>TRANSIENT ANALYSIS CODE ADJUSTMENTS</u>

The code architecture of RELAP5 provides for general heat structure modeling, which can be implemented in cylindrical coordinates with a thermal boundary condition to simulate a cylindrical fuel rod. Several additional models enable representation of dynamic fuel-clad gap conductance, fuel rod swell and rupture, and clad metal-water reaction. The heat structure model relies on user-supplied cold, unstressed geometry in order to solve the conduction equation. Recognizing that the transient is calculated under hot, stressed conditions, an effective gap thermal conductivity is used and is adjusted by multiplying the gap conductance.

Gap conductance is calculated based on the hot, stressed conditions[8] by the cold gap dimension. The solution scheme for the gap conductance calculation includes several opportunities for user input to adjust the solution.

For LOCA analyses the EM applies the following conditions to the steady-state fuel pin model used in R5/M2-BW:

1) A 95/95 VAFT for the hot rod and hot bundle.

2) Fuel pin dimensions and gap gas properties from T3/GDT for the hot rod, hot bundle, and average rod.

The above two conditions impose constraints on the solution of the gap conductance which is solved by the heat transfer routine in R5/M2-BW. In order to make the over-specified problem self-consistent, a gap gas multiplier is introduced on the gap gas conductance term shown in Equation 8 of the TR Supplement. One of the significant inputs to the calculation of the gap gas conductance is the gap width. A scheme has been developed in the EM to apply a correction to R5/M2-BW calculated gap width and make it consistent with the gap width that would have been calculated by T3/GDT. The correction to the gap width is by way of radial correction factors for the fuel pellet outer radius and the cladding inner radius. The following provides a review of the gap gas multiplier and the radial displacement factors.

Implementing the TCD-augmented VAFT in R5/M2-BW causes the fuel mesh point temperatures to increase above the T3/GDT predictions. An adjustment is needed in the R5/M2-BW calculation; otherwise, the increased fuel temperatures will result in overprediction of total heat transfer across the gas gap. This adjustment, in conjunction with the adjusted gap width, is in the form of a multiplier on the gap gas conduction term modeled in R5/M2-BW. Two changes are made in the LOCA EM methodology to determine the multiplier:

- **[**

  **]**

- **[**

  **]**

3.4.1 <u>Gap Gas Multiplier</u>

It is noted that for a given LHR and clad surface convective heat transfer condition the initial or steady-state fuel pellet surface temperature depends strongly on the conductance of the gap between the fuel pellet and the cladding. Though the bias factor f(BU) does not have an explicit dependence on the gap conductance, its implementation in the LOCA initialization requires adjusting the gap conductance, i.e., using the gap conductance as a correction factor, to match the desired 95/95 VAFT and the specified LHR. The correction is done via a multiplier for the gap gas conductance calculated by R5/M2-BW, as discussed in Section 4.2 of the TR Supplement.

---

[8] Based on NRC staff review of Section 2.3.2 of BAW-10164P, all of the gap conductance parameters are calculated using hot, stressed fuel pin conditions predicted at the current time step, including material properties and fuel pin dimensions.

The response to RAI 11 explains the basis for incorporating a gap gas multiplier on the gap gas thermal conductance as shown in Equation 8 of the TR Supplement. The response states,

> [
>
> ]

It is noted that both T3/GDT, as well as COPERNIC2 (but not R5/M2-BW), include an additional term to augment gas thermal conductivity for a close gap. Except for the close gap model, the calculation of the gap conductance is similar among T3/GDT, COPERNIC2, and R5/M2-BW. All of the codes include a term for the gap gas conductance, a term for radiation conductance, and a fuel-clad contact conductance term (no hard contact). Equation 9 of the TR Supplement shows the functional form of the gap gas conductance term that is common to all codes. Two of the geometrical parameters in the gap gas conductance term have direct impact on the magnitude of the gap gas multiplier; they are the gap width and the wall roughness of the fuel pellet and the cladding (inside surface). The gap width is adjusted in R5/M2-BW at the LOCA initialization by applying radial displacement factors (to be discussed below) and the modified gap width is used in the determination of the gap gas multiplier. The response to RAI 11 also shows the functional form of the contact conductance model in R5/M2-BW (not discussed in the TR Supplement). [

].

T3/GDT predicts an open gap for BOL fuel pins. R5/M2-BW typically calculates a [

]. Several seconds after the initiation of a large break LOCA, the combination of fuel cooldown (due to decrease in reactor power) and clad heatup (due to loss of cooling) causes the fuel-clad gap to open and remain open for the remainder of the transient. Previous TIL analyses (with TCD neglected) show that PCT occurs with an open gap. This suggests the gap gas conductivity controls the fuel stored energy removal. In order not to handicap the gap conductivity by a skewed multiplier calculated at steady-state conditions (with a closed gap for MOL and EOL), AREVA modified the procedure to calculate the multiplier. [

]. As discussed in Section 4.2 of the TR Supplement, and further explained in Pages 11-5 through 11-9 of the response to RAI 11, this adjustment enables
[

].

The NRC staff issued RAIs 11 – 13 to develop a better understanding of and justification for the new adjustment process, primarily in order to establish that the new process does not introduce a means for an analyst to reduce analytic conservatism by excessive adjustments to [ ].

The response to RAI 11 addresses the sensitivity of the PCT to the variation of the gap gas multiplier across the range of target values of [ ]. A sensitivity study was performed at BOL, MOL, and EOL[9] using three separate $UO_2$ hot pins with hot spot gap gas multipliers of roughly [ ]. AREVA characterized the results of the sensitivity study by stating that, when the gap gas multiplier is roughly [

]. For the gadolinia fuel, two MOL cases were run, at 2 and 8 weight percent respectively. The limiting PCT changes were about [ ]. The NRC staff reviewed the information provided by AREVA, as supported by data contained in Tables 11-1 through 11-5 of the response to RAI 11. The effects expressed above, e.g., [ ].

The NRC staff also aggregated the data differently, as shown in Table 2, below. In Table 2, the NRC staff treated the [ ] cases as the base case and calculated delta (Δ) PCT values for all of the [ ]. The NRC staff evaluation shows, for the EOL case that had a nominal multiplier of [ ], i.e., per the changed methodology, the one that would require [

]. However, these results are less severe than the unruptured segment PCTs in the EOL analyses and the EOL results are bounded by the MOL results.

---

[9] The TR Supplement, and hence this SE, focus on EM changes needed to address the effects of TCD for MOL and EOL cases. AREVA noted that, should re-analyses be necessary for BOL cases at some point in the future, [ ]. AREVA stated further that such a change would require notification to the NRC in accordance with 10 CFR 50.46(a)(3) requirements. The presented studies provided no evidence to suggest that such a change would be unacceptable, if implemented, however the NRC staff makes no conclusion with regard to these statements.

[ ]

**Table 2. Evaluation of Delta-PCTs Relative to Nominal [ ] Cases.**

The NRC staff review also drew inferences from the adjustments needed for the sensitivity cases to bring the **[** **]**. However, the NRC staff also notes that the **[** **]** are used to bring the gap gas conductance more in line with the more detailed results computed by the fuel performance codes and to do so in a way that has a shorter duration effect on the transient calculation.

Provided the **[** **]**, the adjustment is acceptable. As AREVA states in response to RAI 12, "**[** **]**." The response to RAI 13, discussed further below, also provides additional detail reflecting the modeling approach to **[** **]**. Owing to the somewhat discretionary nature of this adjustment process, in plant-specific submittals to the NRC that are based on the TR Supplement, an NRC technical reviewer may seek information to verify that the analysis was performed in a manner consistent with the response to RAIs 11 – 13.

The sensitivity study presented in the response to RAI 11 also discussed the behavior of the gap conductance and the gap dimension during the LOCA transient. Several general trends are observed in all cases. Within the first several seconds after the accident initiation there is a sharp decrease in the gap conductance due to the loss of contact conductance. The response to RAI 12 notes that, once the contact conduction is lost within the first two seconds of the limiting double-ended guillotine LBLOCA transient (Figure 11-8 and Figure 11-9 of response to

RAI 11), the **[** **]** in the contact conduction equation are no longer used. **[**

**]**.

The response to RAI 11 notes a typographical error in Equation 9 of the TR Supplement. A marked up of Page 4-12 of the TR Supplement is provided in the response and the revised page will be included in the approved version of the TR Supplement.

The determination of gap gas multipliers is part of the approved EM for LOCA analyses. However, the use of **[**

**]**. The response to RAI 13 provides additional description of the adjustment process; such discussion is absent in the TR Supplement. **[**

**]**, which is the subject of response to RAI 21 and will be reviewed in Section 3.4.2 of this SE.

The response to RAI 13 provides additional details on the bases and the procedural steps taken to determine the **[**

]

[

] The response to RAI 14 discusses the effects of this axial variation in the gap gas multiplier.

The response to RAI 14.a notes that the location of the PCT frequently occurs in the peak power location or within one node above or below this location for the 177 fuel assembly, lowered-loop plants, particularly if the PCT occurs in a ruptured node. It also notes that in some previous LBLOCA cases, the unruptured PCT was 2 or 3 nodes away from the peak power location. These shifts away from the peak location generally occur due to the effects of rupture cooling and/or the proximity to a spacer grid. The modified EM performs iterations to achieve a gap gas multiplier value in the range of **[**

**]**. The PCT, however, may occur slightly outside this zone. In response to RAI 14.a, AREVA indicates that in all cases the gap gas multiplier at the PCT location will be reported. AREVA further commits if the gap gas multiplier value at the PCT location does not fall within **[ ]**, then the case will be re-analyzed with the gap gas multiplier adjusted until it falls within this range. The same process will be performed for the gadolinia hot pins.

The effect of the axial variation of the gap gas multiplier on the PCT is demonstrated in response to RAI 14.b. The response used two examples from the response to RAI 11. They are both at MOL, but had different gap gas multipliers throughout the length of the hot pin. In particular, one case has a hot spot gap gas multiplier of **[ ]** and the other has a value of **[ ]**. Despite the difference in multiplier, the two cases resulted in similar overall PCTs. Results from the two example cases suggest that a roughly **[**

**]** difference in PCT. In the general context of the TCD augmentation, the similarities in PCTs from these cases suggest that the effect of axial variation of the gap gas multiplier is small relative to the overall TCD correction and its implementation within the EM.

The response to RAI 14.c confirms the process of determining the hot spot gap gas multiplier for the hot bundle and the average channel, using a similar approach as that developed for the hot pin. The current approved EM uses **[ ]** values to determine the gap gas multiplier. There is no target value for the multiplier. The response to RAI 14.c discusses the impact of different gap gas multipliers for the hot bundle. The impact was investigated by the use of a BOL sensitivity study. By changing the hot bundle hot spot multiplier from **[**

].

The hot bundle sets the fluid conditions for the hot pin and the sensitivity study shows that large variations in the [ ] did not effectively change the overall PCT.

The review described above established that the intended adjustments to [ ] should have a minor impact on predicted PCT. However, the adjustments are necessary to ensure a consistent treatment of fuel stored energy between R5/M2-BW and the fuel performance codes, once augmented for TCD. In addition, the NRC staff also determined that AREVA will use a well-defined process to determine [ ]. Based on these considerations, the NRC staff determined that the adjustments to the [ ] are acceptable.

3.4.2 Radial Displacement Factors

The results from the steady-state fuel pin code provide initial input values to R5/M2-BW for steady-state and transient runs. R5/M2-BW calculates fuel pin geometric dimensions such as the pellet outside and clad inside radii that apply throughout the transient to set the fuel radius for the gap size calculation. The hot radial dimensions of the fuel and the clad calculated by T3/GDT and R5/M2-BW are different in two aspects: 1) the former uses best-estimate fuel temperatures without capturing the effect of TCD while the latter uses TCD-augmented fuel temperatures, and 2) the former includes irradiation-induced geometrical changes resulting from normal operation, while the latter does not. In order to reconcile these dimensional differences, R5/M2-BW calculates radial displacement factors such that the R5/M2-BW calculated radii (fuel outer radius and clad inner radius) achieve the T3/GDT supplied values. These radial displacement factors are applied throughout the R5/M2-BW transient to set the fuel radius and the clad inside radius (while the clad is elastic) for the gap size calculation.

The response to RAI 21.a explains that the approach used to specify the hot fuel geometry parameters in R5/M2-BW based on the steady-state fuel pin code for TCD applications is unchanged from the approved EM. During steady-state initialization, the R5/M2-BW fuel and cladding radii are set via input at each axial location to exactly match the geometry from the steady-state fuel pin code. The response illustrates with figures to show the T3/GDT-calculated hot pin fuel outside and cladding inside radii at BOL, MOL, and EOL. The difference between the R5/M2-BW and T3/GDT fuel pellet outside radius at each axial level, is the fuel over-specification term or fuel radial displacement factor. This term is effectively the irradiation-induced fuel density changes plus any thermal expansion differences from VAFT uncertainties applied to R5/M2-BW. The R5/M2-BW cladding over-specification term, or cladding radial displacement factor, is effectively the cladding irradiation and creep strain contributions used in the steady-state fuel performance code but not in R5/M2-BW.

The response to RAI 21.e explains the bases for maintaining constant radial displacement factors during the LOCA transient. The response states:

> The radial displacement factors force the gap size to be identical to that of the steady-state fuel pin code just prior to initiation of the LOCA transient. As was stated in Part a above, the radial displacement factors are included in RELAP5 to account for burnup dependent geometric differences that occur in the fuel pellet (due to irradiation

density changes) and in the cladding (due to strain effects) that are modeled in the steady-state fuel pin code but not in RELAP5. The irradiation-dependent effects do not change or go away during the short duration of a LOCA transient; therefore, they should be retained (via the constant displacement factor) during the transient calculations. The thermal expansion changes in the fuel or cladding are explicitly modeled in RELAP5. Therefore, any temperature changes are accounted for by RELAP5 in the geometries that control the gap size during the transient.

The response also notes that once the cladding becomes plastic, the clad radial displacement factors are no longer used.

The responses to Parts c and d of RAI 21 provided confirmatory information. The response to RAI 21.c confirms that the radial displacement factors are computed separately for every axial location for each fuel pin modeled (hot pins – including $UO_2$ and gadolinia rods, the hot bundle and the average bundle). The response to RAI 21.d confirms that the modified EM will remain unchanged in the adjustment of R5/M2-BW calculated dynamic gap size via radial displacement factors.

The TCD effect raises the fuel pellet temperatures, leading to variations in thermal expansion of the fuel pellet (as compared to no TCD effect) and affects the fuel pellet radius. The response to RAI 21.b discusses the impact of TCD on the determination and application of radial displacement factors, since the steady-state fuel performance codes (T3/GDT) do not model the effects of TCD and would underestimate the fuel thermal expansion with burnup. In the response, AREVA assessed the impact to be limited. Illustrated in Figure 21-6 of the response are the fuel and cladding radii at MOL and EOL. The figure shows that once the fuel-clad contact occurs there is effectively a constant difference between the fuel and cladding dimensions (i.e. the gap size) that does not change as the burnup continues to increase. The response notes that the two burnups that are potentially most limiting in terms of PCT are either at BOL or MOL. AREVA observes that at BOL there are no TCD-related thermal expansion effects and at MOL there is considerable fuel-cladding contact resulting in the net gap size calculated by the fuel performance code not being impacted by the lack of a degraded thermal conductivity model.

Based on AREVA's demonstration that the potential effects of TCD on the radial displacement factors is minor, the NRC staff concluded that approach used in R5/M2-BW remains appropriate and acceptable for use with the TCD augmentation.

## 3.5 APPLICATION IN EVALUATION MODEL AND DEMONSTRATION ANALYSES

In Section 5 of the TR Supplement, AREVA provides the results of five separate demonstration cases (three at MOL and two at EOL) with and without TCD adjustments. The three cases at MOL include a case using the original EM analysis method without TCD adjustments (as a reference case), a case using the supplement method with TCD compensation, and a case using the supplement method with TCD compensation and reduced LHR. The EOL analyses consist of a case using the original EM analysis method without TCD adjustments and a case using the supplement method with TCD compensation. The MOL and EOL cases with and without the TCD compensations were initialized with different conditions. The analytic conditions and results are summarized in Tables 5-1 through 5-4 of the TR Supplement.

A 177-FA LL B&W plant model with the Mark-BHTP™ fuel was used in the analysis. Since the AREVA LOCA EM is applicable to all three B&W-designed plant types, AREVA stated that the impacts of the modified EM on the transient results are expected to be similar for the 177 FA and 205-FA raised-loop (RL) plants as well. The NRC staff acknowledges that the demonstration results are not applicable to any particular plant and that the TR Supplement methods would need to be applied on a plant-specific basis nonetheless.

The base model used for LBLOCA comparisons includes updates that integrated all the code and method changes consistent with the techniques described in BAW-10179 (Reference 32). The LOCA analyses use approved code revisions along with new methods and error corrections made under 10 CFR 50.46 that are not all identified in Revision 0 of BAW-10192P-A (Reference 1). In particular the TR Supplement cites several NRC-approved TRs that have been incorporated as part of the AREVA LOCA EM for the analysis of fuel with M5® cladding. The LBLOCA analyses also incorporate multiple EM changes made through 10 CFR 50.46 for B&W-designed plant submittals to the NRC to assure that all 10 CFR 50 Appendix K requirements are met.

The R5/M2-BW input model was modified by dividing the reactor vessel control volumes in the upper plenum and upper head in order to model a column weldment (CW) over the hot bundle. During the latter half of blowdown, the core flow reverses and the downward flow and fluid conditions are not as favorable for core heat removal when the hot bundle is located under a CW. The analyses were conducted with both $UO_2$ fuel and gadolinia fuels (2, 4, 6, and 8 percent).

The demonstration cases model a core–inlet-skewed axial peak at 2.506 ft from the bottom of the core. According to the TR Supplement, this core inlet elevation was selected because this is the elevation at which LOCA analyses set the core imbalance limits. In RAI 18, the NRC staff requested information to explain if this elevation is determined from previous LBLOCA analyses and whether this methodology supplement will have any impact on the selection of the elevation for setting the core imbalance limits. The response to RAI 18 indicates that LOCA LHR limits are provided at BOL, MOL, and EOL and at all core elevations (0 to 12 ft) to allow for linear interpolation of limits in the core power distribution analyses.[10] The response clarifies the impact of the TCD on the determination of the LHR limits. It states:

> While TCD will reduce the LOCA LHR limits at times in life after BOL, LOCA analysis will continue to set the LHR limits at core inlet as DNB is not limiting at low elevations in the core. The LOCA analyses with TCD adjustment are expected to reduce the acceptable LOCA LHR peaks at MOL by 5 to 10 percent at all elevations. These TIL and core elevation cases will be performed and provided for use in the core power distribution analyses in order to establish axial offset limits that restrict the axial peaking to less than that used in the LOCA analyses.

---

[10] As noted in Chapter 4 of BAW-10192P-A, five analyses are performed at varying elevations for each TIL.

The response also addresses the potential of the core exit LHR becoming limiting, stating:

> If the core exit LHR becomes limiting, the core power distribution analyses will establish positive axial offsets to values that will restrict the axial peaking that can be obtained. With this understanding, the core exit peaks are not expected to become LOCA limited, but in all cases they will be included in the core power distribution analyses and offset limits set accordingly to limit the allowed axial peaking.

In responding to RAI 18, AREVA confirms that the modified EM will not change the approved methodology to set the offset limits to limit the allowed axial peaking.

The results of the MOL analyses show that PCTs increase significantly with the TCD compensation because of increased initial stored energy. The $UO_2$ hot pin ruptured segment reaches a PCT of 2212 °F (higher than the allowed acceptance criterion of 2200 °F and a 360 °F increase over the case without TCD compensation). The gadolinia hot pins also experience a similar increase in the PCT when the TCD compensation is included in the analysis. AREVA has re-conducted the analyses with TCD compensation but reduced the LHR by 1 kW/ft. The new results show that PCTs are reduced below the acceptance criterion but are still higher than the PCTs evaluated using the original EM methods. The local oxidation and whole core hydrogen generation are slightly increased with the TCD compensation but they are acceptable.

In the EOL analyses, the TCD adjustments also cause increases of PCTs (on the order of 200 °F). The predicted PCTs with the TCD compensation are all below 2200 °F. The TR Supplement notes that COPERNIC2 limits the gadolinia EOL burnup to a rod average of 55 GWd/mtU, while the $UO_2$ fuel has a rod average burnup of up to 62 GWd/mtU. The limit of 55 GWd/mtU was previously not required for analyses using GDTACO, which were carried out to 62 GWd/mtU. Therefore, the reload analysis work supporting the core operating limits report (COLR) restricts gadolinia to 55 GWd/mtU. In order to make the EOL LOCA analyses consistent with the lower burnup limit for the gadolinia fuel the EOL demonstration case with the TCD compensation was done with a composite burnup method. This method analyzes the $UO_2$ hot pin with a rod-average burnup of 62 GWd/mtU, while the gadolinia hot pins and the hot bundle both have rod-average burnup of 55 GWd/mtU. The hot bundle LHR at 55 GWd/mtU is higher and the VAFT or stored energy is higher than a hot bundle at 62 GWd/mtU.[11] This additional stored energy in the hot bundle and higher decay heat supplied to the fuel of the hot bundle penalize the EOL hot pin fluid conditions and reduce the cooling such that a higher PCT is predicted. The composite burnup method is thus a conservative and simpler method than the alternative of running two separate cases with the hot bundle at 55 and 62 GWd/mtU burnup. AREVA states at the end of Section 5.3 of the TR Supplement that if the $UO_2$ EOL PCTs become limiting, then a consistent set of $UO_2$ hot rod and hot bundle conditions can be performed at 62 GWd/mtU.

In RAI 19, the NRC staff requested that the information presented in Tables 5-1 through 5-4 of the TR Supplement should be supplemented to include peak rod burnup and the T3/GDT best-estimate initial peak VAFT as determined using the **[ ]** LOCA initialization. The additional information enables a direct verification of the adjustments to the VAFT at the hot

[11] The NRC staff reviewed COLR content for a B&W plant and observed different sets of LHR limits at three distinct burnup limits for each of the $UO_2$ and gadolinia rods at varying concentrations. The composite method would thus result in a terminal LHR limit at 55 MWd/mtU for the gadolinia rods, while the $UO_2$ LHR limits would extend to 62 GWd/mtU.

spot according to the modified EM to account for TCD effects. In response AREVA provides a markup of Tables 5-1 through 5-4 of the TR Supplement with the requested information. The revised tables will be included in the approved version of the TR.

The above discussion provides a quantification of the overall effect of the implemented TCD modification. Since direct compensation using prior initial conditions causes some PCT results to exceed the 10 CFR 50.46(b)(1) acceptance criterion, clearly a reduction in LHR was necessary.

### 3.6 TCD EFFECT ON SMALL-BREAK LOCA ANALYSES

In Section 4.3 of the TR Supplement, AREVA also describes the SBLOCA transient EM methods and concludes that the effect of TCD increasing the stored energy does not influence the calculated consequences of an SBLOCA. Typically in a SBLOCA, the stored energy in the fuel would have been removed by the time the core uncovers and begins to heat up. Therefore, no changes are needed to the TIL-independent methods of SBLOCA analyses. AREVA does not anticipate performing TIL-specific SBLOCA analyses. If such analyses are needed or requested, AREVA will perform these analyses in accordance with the methods described in the TR Supplement. Since the TCD-related changes would not affect the thermal-hydraulic and system response models used in SBLOCA analyses, the NRC staff did not identify any issues with this approach.

As specified in Section 4.3 of the TR Supplement, explicit SBLOCA analyses for gadolinia fuel are necessary only if the ratio of LHR of gadolinia fuel to $UO_2$ fuel ($LHR_{gad}/LHR_{UO2}$) is not lower than the volumetric heat capacity ratio between the two fuels, $(\rho C_p)_{gad}/(\rho C_p)_{UO2}$. It is noted in the TR Supplement that gadolinia fuel typically has a lower allowed LHR limit compared to that of $UO_2$ fuel.

## 4.0 CONCLUSION

Based on the review discussed in the preceding sections, the NRC staff determined that the proposed modifications to the BWNT LOCA ECCS evaluation model acceptably account for the effects of TCD. Since BWNT LOCA is Appendix K-conformant, the applicable regulatory requirement is that the initial stored energy in the fuel not be underestimated. The effort to develop burnup-dependent augmentation functions and confirm their adequacy, using both experimental data and code-to-code comparisons, demonstrates that the augmented fuel initial stored energy is not underestimated, consistent with the requirements of 10 CFR Part 50 Appendix K. Additional review effort confirmed that modifications to the thermal-hydraulic analysis codes – R5/M2-BW and BEACH – were appropriate to account for the augmented VAFT input. For these reasons, the NRC staff concludes that the TR Supplement is acceptable. The TR Supplement may be considered approved for use by the NRC.

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Attachment: Resolution of Comments

Principal Contributor: B. Parks, NRR/DSS/SNPB

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