AREVA

Response to Request for Additional Information – BAW-10192PA Revision 0 Supplement 1P Revision 0

BAW-10192PA
Rev. 0
Supplement 1P
Rev. 0 Q1NP
Revision 0

Topical Report

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AREVA Inc.

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Nature of Changes

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

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Nomenclature

Acronym	Definition
AC	Average channel
AOR	Analysis of record
BD	Blowdown
BE	Best estimate
B&W	Babcock & Wilcox – AREVA Predecessor
BOCR	Bottom of core recovering
BOL	Beginning of life
BU	Burnup
BWNT	Babcock & Wilcox Nuclear Technologies Company (now AREVA)
CFR	Code of Federal Regulations
CLPD	Cold leg pump discharge
DNB	Departure from nucleate boiling
EM	Evaluation model
EDF	Energy deposition factor
EOB	End of blowdown
EOE	End of event
EOL	End of life
Gad	Gadolinia fuel
Gd	Gadolinia fuel
HB	Hot Bundle
HBC	High burnup chemistry
HP	Hot pin
LBLOCA	Large break LOCA
LHR	Linear heat rate
LOCA	Loss-of-coolant accident
LTR	Licensing Topical Report
M&E	Mass and energy release
MOL	Middle of life
NRC	United States Nuclear Regulatory Agency
OEA	Original EM Analyses
PCT	Peak cladding temperature
RAI	Request for additional information
R5	RELAP5/MOD2-B&W Code
R5/M2	RELAP5/MOD2-B&W Code
RELAP	RELAP5/MOD2-B&W Code
RELAP5	RELAP5/MOD2-B&W Code
RHR	Relative-heat-rating
RIP	Rod internal pressure
S+TCD	Supplement with TCD Compensation
S+TCD+RLHR	Supplement with TCD Compensation & Reduced LHR
SBLOCA	Small break loss-of-coolant accident
SR	Surface roughness

Nomenclature (continued)

SS	Steady state
TCD	Thermal conductivity degradation
TIL	Time in life
TR	Topical Report
VAFT	Volume average fuel temperature

Introduction

The United States Nuclear Regulatory Commission (NRC) provided a request for additional information (RAI) regarding the topical report BAW-10192PA Revision 0 Supplement 1P, Revision 0 (Reference 1) in Reference 2. A total of 21 questions were received from the NRC.

While performing this work, AREVA discovered an error in an equation of the TCD Supplement. This correction is provided in the markup section at the end of this document. Other changes to pages in the TCD Supplement as a result of responses to the NRC questions are also provided in the markup section at the end of the document.

The following sections document the responses to the 21 NRC questions.

1.0 RAI 1

Question:

Reference R-1 lacks a detailed description of the analytic process associated with Babcock & Wilcox Nuclear Technologies (BWNT) loss-of-coolant accident (LOCA), and how this process is modified to perform the input adjustments necessary to account for the effects of thermal conductivity degradation (TCD) within BWNT LOCA. Provide a detailed description of the modified large break (LB) LOCA methodology including a figure showing interfaces between the LB LOCA evaluation model (EM) computer codes and the parameters passed from one code to another.

Response:

Figure 4-1 in BAW-10192P-A, Revision 0, Volume I (Reference 10) depicts the Loss-of-Coolant-Accident (LOCA) high level Evaluation Model (EM) details developed prior to the issuance of BAW-10192PA Revision 0 Supplement 1P Revision 0 (Reference 1). An expanded LOCA EM flowchart is provided in Figure 1—1. While this information is for the entire large break LOCA (LBLOCA) transient, the portions of the LBLOCA analysis that are changed as a result of the modification to the EM to incorporate TCD as documented in Reference 1, only relate to the input to the RELAP5/MOD2-B&W code (Reference 4), generically referred to hereafter as RELAP5. Those portions of the LOCA EM process affected by TCD are shown in yellow on the flowchart.

Volume 1, Section 4.2 of BAW-10192P-A Revision 0 describes the five computer code applications that may be utilized for the LOCA analyses: (1) a steady-state fuel pin code, (2) a blowdown system and fuel pin thermal response code, (3) a system refill and reflood code, (4) a core fuel pin thermal response code (during the refill and reflood phases), and (5) a containment code. The steady-state fuel pin conditions imposed at the onset of the LOCA transient are provided by TACO3 (Reference 5) for UO_2 fuel and GDTACO (Reference 6) for gadolinia fuel.

The output from TACO3 and GDTACO are then supplied as input to the RELAP5 code (Reference 4), which computes the system behavior and fuel pin response during the LBLOCA blowdown phase. REFLOD3B (Reference 12) uses the RELAP5 conditions from the end-of-blowdown to perform the system refill and reflood phases to calculate core inlet and exit boundary conditions. The BEACH code (Reference 9) is simply the RELAP5/MOD2-B&W reflooding core heat transfer models with 2-dimensional rezoning of the fuel pins activated. It uses flooding rates and boundary conditions from REFLOD3 to perform the fuel pin thermal analysis during the system refill and reflooding phases. CONTEMPT (Reference 11) uses mass and energy releases from RELAP5 and REFLOD3 to generate the transient containment pressure and temperature response.

A full LBLOCA analysis typically encompasses running the above sequence of codes eleven separate times to cover all times in life (TIL) and core peak power elevations. Five beginning-of-life (BOL) and five middle-of-life (MOL) UO_2 analyses are performed each at five different core axial peak elevations. The eleventh analysis is performed near end of life (EOL) with a core inlet peak, although the results at this TIL are non-limiting with respect to PCT. The analyzed core axial peak elevations are at the [ ] Each analysis is performed with the prescribed [ ] axial peaking factor. For each case, a nuclear source linear heat rate (LHR) limit is selected to achieve a targeted peak cladding temperature (PCT) of approximately 2000 ± 50 F for the ruptured segments or 2050 ± 50 F for the unruptured segments. The PCT margin at EOL is used to limit the number of EOL analyses; however, results from MOL are used to perform PCT estimates for each of the other four axial levels that are not analyzed at EOL.

Geometrical and property similarities between UO_2 fuel and UO_2 fuel containing gadolinia allow the general LOCA conclusions for UO_2 fuel to be applied to gadolinia fuel. However, the differences in the fuel thermal conductivity between the fuel types are significant enough that the allowed gadolinia LHR must be less than UO_2 LHRs to maintain similar initial volume average fuel temperatures (VAFTs) and PCTs. Therefore, the gadolinia fuel is analyzed at the core inlet power shape at BOL, MOL, and EOL to provide results that can be used to estimate the gadolinia fuel PCTs at the same UO_2 elevations and TILs.

There are multiple codes in the LOCA EM, and the analyses that use these codes are supported by a core power peaking "setup code" and multiple scripts that convert output from one code into input for the subsequent code. The scripts are simple, automated hand calculations that facilitate and expedite the data transfer from one code to the next. They take output in a specific form and units from one code and convert it into the input form and units required for the next code. These automated transfers of data minimize the likelihood of making transposition or calculation errors that could occur during a manual manipulation of the data. These tools do not change the methods described and approved for the codes or the LOCA EM. Details of how this setup code and scripts are used are provided in the following discussion.

The core power peaking setup code is called FUEL3.0. The user provides the initial core power, maximum LHRs for all rods or channels, axial peaking location, axial shape, core pressure, core inlet temperature, and initial core flows to the FUEL3.0 code which then calculates the core power peaking-dependent steady-state core initial conditions (including reactivity feedback and fluid initial conditions). These conditions are then used in RELAP5 at time zero in the LOCA analyses. In addition, FUEL3.0 computes the individual pin and bundle powers needed for RELAP5 and calculates certain input used in the TACO3 (and GDTACO if needed) analyses. The location of the axial power peak and its maximum peaking factor are also used to determine the power peaking dependent input for REFLOD3.

The fuel pin parameters used at time-zero in RELAP5 are calculated for each rod condition and burnup (BU) requested using the TACO3 or GDTACO codes for UO_2 and gadolinia fuel rods, respectively. The parameters calculated are VAFT, hot-expanded fuel outside radius, hot-expanded cladding inside radius, oxide layer thickness on the inside and outside of the cladding, pin internal rod pressure, gap gas composition, radial power profile and fuel-cladding contact pressure. The output from TACO3 or GDTACO is input into RELAP5. Separate calculations are performed for each fuel rod type (i.e., hot pins – both for UO_2 and each gadolinia concentration that is analyzed, hot UO_2 bundle, and average UO_2 channel) to establish the initial fuel rod conditions. The steady-state fuel codes calculate the fuel pin parameters at each of the [ ] axial RELAP5 locations on all fuel rod types used in the model. The VAFT calculated by the steady-state fuel code is increased by a 95/95 uncertainty based on the rod average burnup. BOL analyses use the TACO3 or GDTACO 95/95 hot pin standard uncertainty of [ ] TIL analyses use the generic TCD bias method described in the TCD Supplement, which uses a similar 95/95 uncertainty and includes a hot spot TCD bias based on the rod maximum local burnup to compute the TCD adjusted 95/95 VAFT for the fuel rod.

The fuel thermal conductivity for each fuel rod type to be simulated in the RELAP5 LOCA model is specified by the user based on the targeted rod-average burnup for UO2 as well as individual gadolinia concentrations. This fuel thermal conductivity at BOL is based on an unirradiated BOL value, but if a TIL case is analyzed, the fuel thermal conductivity is updated based on burnup to account for TCD as described in the TCD Supplement, Section 4.2.1(Reference 1).

The nominal [

] in

the regions surrounding the axial peak using the methods specified by the TCD Supplement. This is further discussed in the response to RAI-11.

Once the targeted multipliers are achieved the blowdown analysis is then performed. That is, the RELAP5 code is run from the time of break opening until the end of blowdown (EOB), which is defined as the time when the reactor vessel upper plenum pressure is less than or equal to the containment pressure.

The EOB RELAP5 system output conditions, both inside and outside of the core region, are translated to REFLOD3 input. The decay heat, liquid mass remaining in the reactor vessel or accrued after end of bypass are supplied to REFLOD3 along with the core power peaking. REFLOD3 is then run from EOB until beyond the average core quench time to provide boundary conditions for the BEACH analyses.

If the containment pressure response has not been computed for the current plant equipment and performance parameters, then an iterative process is used to achieve convergence of results based on the RELAP5 and REFLOD3 analyses. First, an initial containment pressure response estimate is applied to RELAP5 for the LOCA blowdown analysis. This pressure estimate can be obtained from a similar plant or previous analysis with variations in the analysis parameters. The RELAP5 boundary conditions at the end of blowdown analysis are supplied to the REFLOD3 code along with the initial containment pressure estimate. The time-dependent mass and energy (M&E) release from RELAP5 and REFLOD3 are then supplied to CONTEMPT to compute a new containment pressure response based on the actual containment analysis. This containment pressure response is used as input in a subsequent RELAP5 blowdown and REFLOD3 analysis. The M&E release from the second set of cases is input to the next CONTEMPT iteration. If the containment pressure responses are nearly identical and within the defined convergence criteria, then convergence has been demonstrated and the containment pressure LBLOCA response is complete. If the RELAP5 blowdown analysis results are converged with the CONTEMPT containment analysis results, but the REFLOD3 reflood analysis results are not, then iteration of only the REFLOD3 and CONTEMPT code can be used to get convergence of those results.

If this iterative blowdown containment pressure response process has been followed previously for a different axial peaking location, or there are no changes in the key plant input or boundary conditions impacting the M&E release from the previous analyzed case, then the containment pressure response from the previous analysis can be used without re-computing the pressure response with a RELAP5/REFLOD3/CONTEMPT iteration. However, if pumped ECCS flows change after the blowdown analysis has ended, a new containment pressure response may need to be computed.

The REFLOD3 analysis produces three key time-dependent boundary conditions that are needed for input to BEACH – (1) core average inlet flooding rate; (2) core inlet subcooling; and (3) reactor vessel upper plenum pressure. These three boundary conditions are extracted from the REFLOD3 analysis and translated as time-dependent volume and junction boundary condition input to the BEACH fuel pin thermal analysis model. The BEACH model is a restart of the RELAP5 analysis from the EOB with most of the RCS deleted and replaced with these REFLOD3-calcualted time-dependent boundary conditions. That is, the entire RELAP5 system model outside the core heated channels along with any crossflow junctions from the core channels and baffle/bypass regions are removed in this restart for the limiting cold leg pump discharge (CLPD) LBLOCA. The core control volumes, junctions, heat structures, and fuel pin gap models are retained from the RELAP5 blowdown model at the EOB time via the restart in BEACH (RELAP5 and BEACH are the topical report names but they both utilize the RELAP5 code). The BEACH analysis is performed from the EOB to the end of the event (EOE), which is 10 seconds after the BEACH average core quench time. BEACH calculates the PCTs and core oxidation for all rod types and gives the details used to calculate the overall core hydrogen generation.

If the BEACH results do not meet the 10 CFR 50.46 acceptance criteria, then the LHR must be reduced and the entire LBLOCA analysis re-performed. If the PCTs do not fall within the requested targeted ranges, then the LHR may be adjusted up or down as needed within the power range limitations placed on the EM or EM codes to achieve the targeted range.

Figure 1—1 LBLOCA Evaluation Model Flow Map

2.0 RAI 2

Question:

During the audit documented in Reference R-2, the NRC staff reviewed calculation notebooks that provided a detailed discussion of the characteristics of each fuel performance code case that was used to determine the TCD bias function that is applied to the TACO3 (Reference R-3) and GDTACO (Reference R-4) initialization parameters (i.e., initialization parameters that are supplied to RELAP5/MOD2-B&W, Reference R-7). These descriptions are important to justify that the adjustment is based on a sufficient set of cases to provide a bounding representation of cycle operation, as are accompanying power history, or linear heat rate (LHR) limits. The TR does not provide any discussion of the cases and the LHR limits shown in Figures 3.1 through 3.6 and Figure 3.8. Provide detailed discussions about them.

Response:

The data presented in Figure 3-1 through Figure 3-6 and Figure 3-8 of the TCD Supplement (Reference 1) were generated with a series of cases analyzed with TACO3/GDTACO and COPERNIC2 for each individual fuel type. The following sections describe each case and include the rod power history and the axial power shape. As TACO3/GDTACO cases and COPERNIC2 cases are meant to model the same scenarios, only descriptions of the TACO3/GDTACO cases are provided below.

The "LHR limit" presented in Figure 3-1 through Figure 3-5 of the TCD Supplement represents a typical example of the peak LHR used in the LBLOCA PCT evaluation. These figures demonstrate that the range of nodal burnup and nodal LHR analyzed in the series of cases used to determine the generic TCD bias functions adequately bounds the expected range of application.

UO_2

UO_2 Power Histories

It should be noted that TACO3 does not linearly interpolate between burnup steps but implements a stair-step change between burnup steps. The power histories shown in Figure 2—3 are a visual representation of the power histories but do not portray the exact implementation in the code solution.

2wt% Gad

2wt% Gad Power Histories

It should be noted that GDTACO does not linearly interpolate between burnup steps but implements a stair-step change between burnup steps.

The power histories shown in Figure 2—5 are a visual representation of the power histories but do not portray the exact implementation in the code solution.

4wt% Gad

[ ]

6wt% Gad

[ ]

8wt% Gad

[ ]

[ ]

Table 2—1 UO_2 Case 1 Axial Power Shape

[ ]

Table 2—2 UO_2 Case 2 Axial Power Shape

Table 2—3 2wt% Gad Case 1 Axial Power Shape

Figure 2—1 UO_2 Case 1 Axial Power Shape

Figure 2—2 UO_2 Case 2 Axial Power Shape

Figure 2—3 Power Histories for UO_2 Cases

Figure 2—4 2wt% Gad Case 1 Axial Power Shape

Figure 2—5 Power Histories for 2wt% Gad Cases

3.0 RAI 3

Question:

The applicability limits provided in Table 3-4 of Reference R-1 are based on calculation files supporting the development of the topical report (TR). Compare the basis against the applicability range of the computer codes (COPERNIC2, (Reference R-5), TACO3 and GDTACO) and experimental data used in the development of the TCD bias functions.

Response:

The applicability limits for the generic TCD bias functions provided in Table 3-4 of the TCD Supplement (Reference 1) were based on the range of fuel design parameters and operating conditions used in the following:

- calculation of the TCD bias functions (Section 3.1.2 of the TCD Supplement),
- code-to-code validation cases (Section 3.2.1 of the TCD Supplement), and
- comparisons to measured data from experimental fuel rods (Section 3.2.2 of the TCD Supplement).

The TCD bias functions and the code-to-code validation cases were based on the Mark-BHTP™ fuel rod design and focused towards high LHRs typical of LOCA initialization analyses. Comparisons to the measured experimental data were used to validate the generic TCD bias functions across a more diverse set of fuel design parameters; [ ] The measured data comparisons demonstrate that the generic TCD bias functions are conservative for the different fuel rod designs [ ] As discussed in the Response to RAI-4, the form and functionality of the generic TCD bias functions results in a very conservative penalty at lower LHR and progressively become more accurate at higher LHR.

[

] See the Response to RAI-6.a for additional discussion.

Based on the preceding discussion, a more limited range of application for the generic TCD bias functions will be implemented. The generic TCD bias functions were calculated for use at the hot spot of the current Mark-BHTP™ fuel rod design.

Validation cases from Section 3.2.1 of the TCD Supplement (Reference 1) and the additional validation cases presented in the Response to RAI-6.a are also based on the current Mark-BHTP™ fuel rod design. Therefore, the applicability limits for the generic TCD bias functions will be based on the nominal design parameters for the current Mark-BHTP™ fuel rod design. Table 3—1 lists the recommended applicability limits for the generic TCD bias functions. See the Response to RAI-5 for additional comparison of the Mark-BHTP™ fuel design in use at each B&W plant.

It is important to recognize that the applicability limits in Table 3—1 are only germane to the generic TCD bias functions. These should not be interpreted as limitations on the methodology to generate the TCD bias functions or on the direct code-to-code comparison methodology described in Section 3.3 of the TCD Supplement (Reference 1). Overall, the TCD bias methodology is limited by the application ranges of the fuel performance codes TACO3/GDTACO and COPERNIC2. Table 3—2 lists the relevant application ranges for the fuel performance codes.

A comparison of the revised generic TCD bias functions range of applicability in Table 3—1 with the TACO3/GDTACO and COPERNIC2 range of applicability in Table 3—2 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 also provides the key design parameters of the experimental fuel rods used in the validation of the generic TCD bias functions.

A markup of Table 3-4 in Reference 1 is provided in the markup section at the end of this document. Table 3-4 will be revised as shown in the markup page in the approved version of the topical report.

Table 3—1 Limits of Applicability for Generic TCD Bias Functions

Table 3—2 Fuel Performance Code Application Limits

[ ]

Table 3—3 Design Data of Experimental Fuel Rods

4.0 RAI 4

Question:

The trending illustrated in Figure 3-10 indicates [

] Provide the evidence that [

]

Response:

Figure 3-7 of the TCD Supplement (Reference 1) shows that the magnitude of degradation in thermal conductivity is a combined effect of the burnup and the fuel temperature (or linear heat rate). The generic TCD bias functions are formulated [

] This is best visualized by the range of TCD bias at a given burnup in Figure 3-6 of the TCD Supplement. [

]

This causes the generic TCD bias functions to be very conservative at low LHR and progressively become more accurate as the LHR increases. Therefore the observed trends [

]

The COPERNIC2 code has been validated to a much broader database of measured data than those presented in Figure 3-10. Hence, the code-to-code validation cases present a more comprehensive perspective of the overall conservatism of the TCD bias functions.

The code-to-code validation cases from Section 3.2.1 (Table 3-3) of the supplement (Reference 1) and the additional validation cases presented in Response to RAI-6.a demonstrate that the TCD bias functions adequately penalize TACO3 and GDTACO VAFT predictions at the hot spot over the target range of LHR (see Table 3—1) for LOCA initialization applications.

5.0 RAI 5

Question:

During the audit the NRC staff indicated that information sufficient to compare the validating data used in Reference R-1 to current-generation fuel designs in use at Babcock and Wilcox (B&W) nuclear power plants would be necessary. In the response the vendor suggested that such data, regarding the Mark B-HTP fuel design, is available in the current revision of BAW-10179 (Reference R-6). Explain how the data varies for the B&W nuclear power plants.

Response:

Table 3-1 of the current revision of BAW-10179 (Reference 8) shows an older generation of the fuel rod design. [

] Table 5—1 shows the fuel design characteristics used in all Babcock and Wilcox (B&W) nuclear power plants. There is currently no variation in the fuel characteristics between the plants. The values of the parameters in Table 5—1 are consistent with those in Table 3—1 and thus the generic TCD bias is applicable to the current fuel design in the B&W plants.

Table 5—1 Fuel Rod Characteristics

6.0 RAI 6

Question:

The TR utilized a comparison between calculated fuel centerline temperature plus TCD bias function and measured fuel centerline temperature to conclude that the TCD bias functions have adequately penalized the TACO3/GDTACO fuel temperature predictions. It is not readily apparent to the NRC staff that such a comparison leads to the conclusion in the TR. Provide the following additional information.

a. Additional justification that applying a bias function based on the [

] for the LOCA initialization.

b. Explanation of the process of transforming the VAFT from TACO3 to RELAP5-BEACH (Reference R-7) heat structure initial temperatures, which includes comparison of the following VAFTs across the core axial elevation for the hot pin: TACO3 best-estimate, TACO3 upper tolerance limit, COPERNIC2 best-estimate, COPERNIC2 upper tolerance limit, TACO3 adjusted additively, and TACO3 with the TCD bias ratio applied.

c. Descriptions and comparisons similar to the ones discussed in Item b, comparing the hot pin adjustment to the hot bundle adjustment.

d. The plots in the presentation during the audit showing the [

] to clarify the application of a [

] The plots should include more data (purple dots) to compare against the solid gold line as shown on Page 31 of presentation.

Response:

Part a:

In RELAP5, reconstruction of the radial temperature profile in the fuel pellet requires three components. First, the VAFT must be adequately penalized for TCD effect. The generic TCD bias functions are constructed to assure that the VAFT has been penalized such that the bounding predictions from TACO3/GDTACO are conservative relative to the 95/95 predictions from COPERNIC2. Validation cases from Section 3.2.1 (Table 3-3) of the TCD Supplement (Reference 1) demonstrate that the TCD bias functions adequately penalize TACO3 and GDTACO VAFT predictions in the target range of LHR for LOCA initialization applications.

Second, an accurate model of the radial power distribution in the fuel pellet is needed. The radial power distribution in the fuel pellet is not affected by TCD and the predicted radial profiles from TACO3/GDTACO remain applicable (see Section 3.4 and Table 3-5 in the TCD Supplement, Reference 1).

Lastly, the fuel thermal conductivity must be representative of the temperature and burnup conditions to be analyzed. Section 4.2.1 of the TCD Supplement (Reference 1) discusses modifications to the fuel thermal conductivity modeling in RELAP5 to initialize the LOCA analyses. Figure 4-5 of the TCD Supplement shows the impact of the changes and the correct reconstruction of the radial temperature distribution in the fuel pellet.

In Section 3.2.2 of the TCD Supplement (Reference 1), TACO3 and GDTACO predicted fuel centerline temperatures were compared with measured centerline temperatures from experiments. Comparisons to the measured experimental data were used to validate the generic TCD bias functions across a more diverse set of fuel design parameters; however, the measured data covers a lower range of LHR than is typically analyzed for LOCA initialization.

The TACO3 and GDTACO predictions were penalized using Equation 7 (Reference 1) [ ] The application of Equation 7 [ ] As discussed in the Response to RAI-4, the form and functionality of the generic TCD bias functions results in a very conservative penalty at lower LHR. [ ] The Response to RAI-3 implements a reduced range of application for the generic TCD bias functions.

The objective of the generic TCD bias functions is to penalize TACO3 and GDTACO VAFT predictions to be greater than or equal to the COPERNIC2 95/95 VAFT predictions. COPERNIC2 has been validated to experimental data covering a wide range of LHR and burnup. This validation includes the [ ]

Section 3.2.1 of the TCD Supplement (Reference 1) presents code-to-code validation cases between TACO3/GDTACO and COPERNIC2 demonstrating that the TCD bias functions conservatively meet the objective. To augment this, ten additional code-to-code validation cases were run. These 10 cases cover additional gadolinia concentrations and a larger range of linear heat rate for each fuel type.

All of the validation cases model the current Mark-BHTP™ fuel rod design in use at the B&W plants (see Response to RAI-5). The results from the full suite of validation cases are shown in Table 6—1. For each case the penalized TACO3/GDTACO VAFT is greater than the 95/95 VAFT from COPERNIC2.

Part b:

The LOCA EM uses TACO3 (Reference 5) and GDTACO (Reference 6 - for gadolinia fuel) to provide fuel pin initial geometry and thermal values prior to the initiation of the LOCA to establish the steady-state core conditions in RELAP5 for performing LBLOCA analyses (see response to RAI 1). TACO3 and GDTACO produce best-estimate VAFTs and fuel pin initializations. The VAFTs are increased to account for uncertainty when used in the RELAP5 analyses to ensure conservative fuel stored energy contributions are applied in the core. At BOL, a hot pin uncertainty of [ ] percent (Appendix I of Reference 5) is sufficient since the fuel thermal conductivity has not yet degraded from irradiation. The lack of TCD models in these codes requires that the VAFTs computed at TIL be increased by more than an uncertainty of [ ] percent for the purpose of producing the maximum PCTs during a LBLOCA. Adequately addressing TCD for TIL cases in the LOCA EM analyses requires identifying an appropriate increase in VAFTs for the purpose of specifying stored energy input to the RELAP5 fuel pin model.

Adequately addressing TCD with TACO3 and GDTACO can be accomplished by one of two methods. The primary method (described in Reference 1, Section 3.0) is to develop a generic TCD bias factor that can be applied to a TACO3 VAFT at the highest temperature location (hot spot) to ensure a bounding VAFT is used in the LOCA analysis. This method uses a generic TCD bias factor as a function of burnup that when combined with the steady-state fuel code 95/95 VAFT uncertainty produces conservative fuel stored energy input at any TIL.

This approach is the preferred method as it requires fewer steady-state fuel analyses to establish the LOCA initial conditions; however, as detailed in this RAI response, it does introduce considerable conservatism in locations other than the hot spot and in lower power rods including the high concentration gadolinia rods. As a result of these considerations an alternate direct code-to-code method also exists (described in Reference 1, Section 3.0). This method requires running comparable TACO3 and COPERNIC2 (Reference 7) cases at the specific TIL for each fuel rod type and developing VAFT input to match the COPERNIC2 95/95 VAFTs. Both of these methods are discussed in further detail in the following paragraphs.

When TCD is accounted for by using the generic TCD bias method, the approach for setting the hot spot RELAP5 VAFT is performed as described in Section 3.1.2 of the TCD Supplement (Reference 1) and summarized here. Additional information and detail is provided in this RAI to define how to adjust the VAFTs at locations other than the hot spot (i.e. along the entire fuel rod).

The first step is to run a TACO3 (or GDTACO) case at the rod-average burnup requested. From this run, the peak local burnup anywhere on the rod is determined. This maximum burnup is then used to interpolate in Figure 3-6 (for UO_2 fuel) or Figure 3-8 (for gadolinia fuel) of the TCD Supplement 1 (Reference 1) to obtain the proper TCD bias to apply to the hot spot VAFT from TACO3. When the entire rod is examined, the burnup obtained will produce a bias that is conservative for the hot spot and more conservative than needed for all lower burnup regions on the fuel rod.

By way of example, a TACO3 case analyzed for a hot pin at the 2.506-ft elevation with a 17.8 kW/ft nuclear source LHR. Figure 6—1 shows the TACO3 best-estimate (BE) prediction with the 95/95 uncertainty of [ ] percent on the VAFT in degrees Fahrenheit shown as error bars. No TCD bias factor is included on this curve.

In this case, the local burnup at the peak fuel temperature was [ ] This burnup was rounded up to [ ] and the UO_2 TCD bias function from Figure 3-6 of the TCD Supplement was determined to be [ ] The TACO3 95/95 TCD adjusted temperature for the hot spot of the hot pin is computed as follows.

Eqn. 6-1

[ ]

This is the highest temperature along the rod and it is represented by the purple dot shown on Figure 6—1.

This example is further used to illustrate the process for extending the adjustments to the rest of the fuel rod. Two separate sets of VAFT calculations were performed and the results were also plotted on this figure. The gold dashed line is the TACO3 BE VAFT multiplied by [ ] and [ ] added to the result at each axial level along the rod. The solid gold line is the TACO3 BE VAFT adjusted by a ratio of the TCD biased 95/95 VAFT at the highest value divided by the TACO3 BE VAFT at this location. As calculated in Eqn. 6-1, the TCD biased 95/95 VAFT is [

]

Eqn. 6-2

[ ]

This hot spot ratio was used as though it was a UO_2 hot pin VAFT uncertainty multiplier of [ ] which was then multiplied by each TACO3 BE VAFT in degrees Celsius at each axial level to get the 95/95 TACO3 VAFT values, which account for the VAFT uncertainty and the TCD bias. These temperatures were converted back to degrees Fahrenheit for input to RELAP5 and for the comparisons shown in Figure 6—1.

Each of these processes to account for TCD and the 95/95 VAFT uncertainty are valid; however they produce considerable differences for the lower power regions of the rod. Additional information is needed to determine the most appropriate approach that should be used for the entire rod. This is determined by a comparison of the axial temperature distribution to those of COPERNIC2 that has the TCD included in its formulation.

The green trace in Figure 6—2 shows the COPERNIC2 best-estimate VAFTs for a hot pin at 17.8 kW/ft nuclear source LHR with a 2.506-ft elevation peak. In this figure, error bars indicate the COPERNIC2 95/95 uncertainty of [ ] added to the VAFTs at each axial level. If the direct code-to code comparison was used, the uncertainty adjusted VAFTs from COPERNIC2 would be supplied as input to RELAP5 at each axial level. Therefore, these are the VAFTs that should be achieved to account for TCD.

The two possible TACO3 95/95 VAFTs with TCD biases from Figure 6—1 are compared to the 95/95 VAFT results from COPERNIC2 to determine which approach most closely align. Figure 6—3 shows the comparison of the COPERNIC2 95/95 VAFT versus the TACO3 multiplicative ratio approach. Note that the core elevations are slightly shifted due to the thermally expanded axial elevation differences between the two codes. Based on this comparison, it is clear that the multiplicative ratio approach accurately predicts the stored energy in the fuel and should be used to determine the 95/95 VAFTs over the remainder of the axial locations when the generic TCD bias method is used.

When gadolinia rods are used, they are modeled as separate hot pins. The same approach described above to calculate the hot spot hot pin UO_2 TCD adjusted VAFTs with the generic TCD bias function option is used for the gadolinia rods. Note that the generic gadolinia TCD bias function is based on Figure 3-8 of the TCD Supplement (Reference 1).

If the code-to-code direct comparison approach is used, the RELAP5 VAFT input will exactly match the case specific COPERNIC2 best-estimate VAFT plus the 95/95 uncertainty of [ ] at each axial level.

Eqn. 6-3

[ ]

In the example case described, the TACO3 case had burnups between [ ] in the eight axial segments above the hot spot. If these burnups were rounded up and used to obtain a generic TCD bias factor, it would increase to a maximum of [ ] versus the [ ] used. However, as can be seen in the comparison plots in Figure 6—3, the generic TCD bias VAFT input is already higher that the COPERNIC2 95/95 VAFT. Therefore, use of the [ ] higher TCD bias factor is additional conservativism that is unnecessary to include in the demonstration cases. However, future generic TCD bias licensing cases will use the maximum burnup on the rod (as reiterated in the response to RAI 10) to establish the additional VAFT increases. If the generic TCD bias approach is not used, a specific code-to-code comparison case is performed to reduce the conservatisms imposed by the generic bias approach.

Part c:

When the generic TCD bias function is being used, new COPERNIC2 analyses are not performed. However, the hot bundle uncertainty is developed based on the best-estimate COPERNIC2 hot spot VAFT. Therefore, without a COPERNIC2 analysis, an effective hot spot best estimate temperature is computed from the UO_2 hot pin VAFT that has been adjusted based on uncertainty and the generic TCD bias function as described in the response to Part b above. This effective best estimate VAFT is computed by using the hot pin, hot spot VAFT from Eqn. 6-3 and rearranging it as follows:

Eqn. 6-4

[ ]

The hot bundle 95/95 VAFT at the hot spot is computed by multiplying the best-estimate COPERNIC2 temperature times [ ] based on the information provided in Section 4.1 of the TCD Supplement.

Eqn. 6-5

[ ]

A similar approach that was used to compute the hot pin VAFTs versus elevation (described in the Part b response) is used to develop the 95/95 UO_2 TCD adjusted VAFT for the hot bundle when the generic TCD bias function option is used. A multiplicative factor for the hot bundle will be determined based on the ratio of the COPERNIC2 hot bundle 95/95 VAFT (calculated using Eqn. 6-5) to the TACO3 hot pin best-estimate temperature at the hot spot similar to that performed for the hot pins.

Eqn. 6-6

[ ]

This multiplicative factor computed by Eqn. 6-6 will be applied to the TACO3 temperatures at all fuel axial locations to set the 95/95 VAFTs for the hot bundle when the generic TCD bias approach is used.

Eqn. 6-7

[ ]

These VAFTs will be converted back to degrees Fahrenheit for input to the RELAP5 LOCA model.

If the generic TCD bias method is not used, then a COPERNIC2 LOCA initialization has to be performed. In this case, the hot spot best-estimate temperature from COPERNIC2 is directly available and it can be substituted into Eqn. 6-5 and the remaining calculations performed to set the RELAP5 VAFTs for the entire hot bundle.

Part d:

The response to Part b of this RAI provides the information requested at each axial level. The plots in the presentation did not show all the elevations as data points, but they were included in the figures shown. Figure 6—2 in this RAI shows the 95/95 VAFTs for COPERNIC2. Figure 6—3 of this RAI compares those 95/95 COPERNIC2 VAFTs to the TACO3 TCD adjusted (aka RELAP5 input VAFTs) at each axial level.

Table 6—1 Validation Case Results

Figure 6—1 TACO VAFTs

Figure 6—2 COPERNIC2 VAFTs

Figure 6—3 TACO3 TCD Bias Multiplicative Ratio versus COPERNIC2 95/95 VAFTs

7.0 RAI 7

Question:

Section 3.1.2.1 of Reference R-1 states that the generic TCD bias function is developed with cases [ ] This is inconsistent with the approved LOCA initialization methodology. Provide the explanation of why this is acceptable.

Response:

The objective of the TCD bias function is to ensure that the penalized volumetric average fuel temperature (VAFT) from TACO3/GDTACO is always greater than or equal to the uncertainty adjusted 95/95 VAFT from COPERNIC2. The approach chosen by AREVA to ensure that the penalized VAFT from TACO3/GDTACO is always greater than or equal to the uncertainty adjusted 95/95 VAFT from COPERNIC2 was to:

[ ]

The validation cases (presented in Reference 1) validate that the penalized VAFT from TACO3/GDTACO is always greater than or equal to the uncertainty adjusted 95/95 VAFT from COPERNIC2 [ ] Therefore, the selected methodology is conservative.

8.0 RAI 8

Question:

It is necessary to perform a sufficiently complete evaluation of the [ ] modeling option employed for LOCA initializations using TACO3 and GDTACO, which were added after NRC staff approval of the TACO3 and GDTACO fuel performance methods.

a. Provide comparisons among TACO3 and GDTACO, TACO3 and GDTACO with [ ] and COPERNIC2 at middle-of-life and end-of-life conditions, as well as experimental data if available, for LOCA-initialized fuel pins. The comparisons should include radial power distribution, VAFTs, cladding inner radii, fuel outer radii, pin pressure, pin gas composition, oxide thickness, and final plenum volume.

b. Clarify the term " [ ] " in the first paragraph on page 5-4 of Reference R-1. This term seems to mean the " [ ] " "based on the LBLOCA analysis methodology discussed in the TR, but the term itself implies that [ ] of the LOCA initializations.

Response:

<u>Part a:</u>

The requested comparisons are provided in Table 8—1 through Table 8—7 and Figure 8—1 through Figure 8—6.

The effect of [ ] hold time in TACO3/GDTACO is to increase the VAFT, the fission gas release, and the rod pressure. The results in Table 8—1 show that the penalized TACO3/GDTACO 95/95 VAFT predictions are conservative relative to COPERNIC2 regardless of the treatment of [ ] during the hold time. Rod pressure and fission gas release are either conservatively calculated by TACO3/GDTACO for the LOCA application or have a negligible impact on the LBLOCA PCT versus use of COPERNIC2 parameters that have TCD included. There is little or no impact on the radial power distribution, the fuel and cladding dimensions, and the plenum volume. Section 3.4 and Table 3-5 of the TCD Supplement (Reference 1) also include additional discussion for each of these parameters. The TACO3/GDTACO LOCA initialization analyses [ ] are addressed by the use of a "penalty" applied to the best estimate VAFT results to achieve the 95%/95% one-sided upper tolerance limit temperature (Section 5 of Reference 5).

While there are no specific experimental data available for LOCA-initialized fuel pin temperatures, COPERNIC2 has been validated to experimental data covering a wide range of LHR and burnup. This validation includes [ ] The power ramp tests include a peak LHR of [ ]

The LOCA initialization methodology simulates a ramp to high local LHR and these conditions are held for a time period of several hours. [

]

Part b:

The methods used for performing LOCA initializations prior to the TCD Supplement (Reference 1) allowed the clad to creep during the [ ] hold period for the TIL LOCA initializations. The term [ ] means that at MOL or EOL the cladding continues to creep or expand outward, potentially reducing the fuel cladding contact pressure and/or reopening the gap size because there was an outward hoop stress. For future LOCA initializations, no clad creep will be allowed during the LOCA initialization hold period as described in TCD Supplement Section 3.1.1.2. Use of no clad creep option in TACO3 produces conservative VAFT results relative to COPERNIC2 when appropriate TCD bias uncertainty penalties are implemented. When no creep is allowed during the [ ] hold period, the cladding creep does not change. Therefore, this method was called the [ ] option.

Table 8—1 Volume Averaged Fuel Temperature Comparisons

Table 8—2 UO_2 Pin Gas Composition Comparisons

Table 8—3 2wt% Gad Pin Gas Composition Comparisons

Table 8—4 8wt% Gad Pin Gas Composition Comparisons

Table 8—5 UO_2 Fuel Pin Parameter Comparisons

Table 8—6 2wt% Gad Fuel Pin Parameter Comparisons

Table 8—7 8wt% Gd Fuel Pin Parameter Comparisons

Figure 8—1 UO_2 MOL Radial Power Comparison

Figure 8—2 UO_2 EOL Radial Power Comparison

Figure 8—3 2wt% Gd MOL Radial Power Comparison

Figure 8—4 2wt% Gd EOL Radial Power Comparison

Figure 8—5 8wt% Gd MOL Radial Power Comparison

Figure 8—6 8wt% Gd EOL Radial Power Comparison

9.0 RAI 9

Question:

Apparently, TACO3, GDTACO, and COPERNIC2 do not use common temperature units. While TACO3 and GDTACO use degrees Fahrenheit (°F), COPERNIC2 uses degrees Celsius (°C). Explain clearly the temperature units used in computation, and those used in developing bias functions. Then justify the applying ratios that are based on non-absolute temperature units (i.e., °F and °C have arbitrary zero values, whereas Kelvin (K) and Rankine (R) are the corresponding absolute temperature scales) because the use of different temperature units will result in different values for the VAFT axial adjustment ratio.

Response:

For computation TACO3 and GDTACO use degrees Fahrenheit (F) and COPERNIC2 uses degrees Celsius (C). Since the native unit of temperature in TACO3/GDTACO is F the TCD bias was developed in that unit as well. Eqn. 9-1 shows the form of the TCD bias functions.

Eqn. 9-1

[ ]

The f(BU) term is calculated by solving the inequality on the right hand side of Eqn. 9-1 using the predicted VAFTs from TACO3/GDTACO and COPERNIC2 with the results of COPERNIC2 being converted to (F). For a given fuel type, the value of f(BU) is plotted versus the corresponding nodal burnup and a curve of f(BU) versus nodal burnup is defined that bounds all of the plotted data.

Discussion of the ratio application is provided in response to question 6b. Discussion of the process is described in response to question 6c.

10.0 RAI 10

Question:

Figure 5-18 of Reference R-1 shows the [

] However, they are different from those in Figures 3-1, 3-2, and 3-5. The differences are not only in the [

] Provide discussion to clarify the differences and explain the significance of distinguishing the figures by [

]

Response:

One of the primary uses of the LOCA analyses is to provide peaking input limits to the fuel reload process. The key input for the core power distribution analyses is a nuclear source LHR that represents all the power produced in the fuel at the peak power location. The total power produced in the core is the nuclear source. Most of this nuclear source energy is deposited in the fuel or cladding, but there is a small fraction that is absorbed directly by the moderator. Therefore, an accurate description of what the power peaking includes is important. The LOCA peaking is defined in terms of the nuclear source peaking and rod average burnup.

The LOCA analysis is performed at the nuclear source LHR to produce a PCT. The input to the LOCA analysis requires fuel pin initial conditions, which are provided by an NRC-approved fuel pin performance code (e.g., TACO3, GDTACO or COPERNIC2). The fuel pin code computes the thermal response in the fuel, so it uses the thermal power generated in the fuel pin for its analysis. This thermal power (i.e. energy deposited in the fuel) is lower than the nuclear source power, because there is some direct energy deposition into the moderator, primarily from the hydrogen nucleus-neutron collisions that slow down the neutrons.

The difference in the nuclear source LHR and the thermal power is defined as the energy deposition factor, or EDF.

Eqn. 10-1

[ ]

The LOCA analysis is also performed at the rod average burnup. The steady-state fuel pin codes are run such that they target the same rod average burnup. These codes simulate a rod operating at typical power history peaking with both radial peaking and an axial power shape supplied as a function of burnup. This normal full power operation is simulated until the rod achieves the desired burnup at which the LOCA occurs. The burnup axially along the rod at the time of the LOCA initialization reflects an integrated axial power distribution during these days of operation. Locations near the middle of the rod will have higher burnups than the rod average, because of the axial power shape, which leads to lower powers and burnups away from the peak power location. Typically, the peak burnup on the rod at MOL to EOL is 15 to 20 percent higher than the rod average burnup. 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.

The considerations described above become elements in portions of the LOCA initialization and transient LOCA analysis. The presentation of the results can take various forms. A numerical example is provided to help illustrate how the differences in the nuclear source and thermal LHRs and the rod average to local burnups used in the analysis for the MOL LOCA case.

Figures 3-1 through 3-8 and Figure 5-18 of the TCD Supplement (Reference 1) are taken from the same UO_2 MOL LOCA demonstration case. In Figure 5-18 (Reference 1), the results are presented in the form of rod average burnup [

]

To summarize, Figures 3-1 through 3-8 of the TCD Supplement (Reference 1) are based on nodal or local burnup in the fuel rod. Figure 5-18 is based on fuel rod-average burnup. The steady-state axial power shapes used during plant operation establish the integrated burnup locally versus on a rod average basis. It is not uncommon to have a maximum local burnup on a rod that is roughly 15 - 20 percent greater than the rod average burnup. In the examples cited by this RAI, the local, or nodal, burnup is [

]

11.0 RAI 11

Question:

With regard to the [ ] discussed in Section 4.2.2 of Reference R-1, the following additional information is requested in order to continue its review.

a. Sensitivity studies varying the gas gap multiplier across the range of target values ([ ]) showing the following results: predicted cladding temperature behavior including the peak cladding temperature (PCT), gap conductance, and gap dimension.

b. Consideration, within the sensitivity studies discussed above, for variability in fuel cladding plastic deformation and rupture behavior, and for varying Gadolinia concentrations.

Response:

Executive Summary for Part a:

The BOL and MOL LOCA evolutions with different gap gas multipliers achieved via [ ] adjustments had similar results and trends within the targeted gap gas multiplier range. The gap dimensions (considering swelling and rupture) varied slightly with gap gas multiplier, but were not substantially different and did not lead to significant changes in PCT. At BOL, the overall PCT changes are less than [ ] change in gap gas multiplier. At MOL, the overall PCTs are within [ ] change in multiplier. At EOL, the PCTs are within [ ] multiplier change, although these PCTs with the reduced EOL LHRs are not limiting as they are more than [ ] below the limiting MOL values.

The ideal gap gas multiplier is [ ] at the hot spot location. Adjustments to the nominal [ ] input as defined in the response to RAI 13 can be made to modify the gap gas multiplier. No input adjustments are required if the multipliers are between [ ] however, adjustments are required if the multiplier is outside this range. Adjustments to the [ ] input are permitted and they are used to push the gap gas multipliers closer to [ ] (not the far multiplier extreme) even if they are in the targeted range.

When adjustments are performed, the goal is to push the multiplier closer to [ ] When the gap gas multiplier is roughly [

]

Executive Summary for Part b:

The fuel and cladding LOCA evolutions for gadolinia fuel with different gap gas multipliers achieved via [ ] had similar results and trends as the UO_2 fuel within the targeted gap gas multiplier range. The gap dimensions (considering swelling and rupture) varied slightly with gap gas multiplier, but were not substantially different and did not lead to significant changes in PCT. For both the 2 and 8wt% gadolinia fuel at MOL, the limiting PCT changes were less than [ ] change in gap gas multiplier. For the cases performed to address this RAI response, the gap gas multipliers are within the targeted range and do not need to be adjusted. Adjustment is permitted; however, and if used the multiplier is pushed closer to [ ] (not to the multiplier extreme on the opposite side of [ ]). Should the gap gas multipliers fall just outside the targeted range, an adjustment is required to push them back into the range where the value is closer to [ ]

Similar to the UO_2 fuel, if the multiplier is just greater than [

]

Detailed Response Part a:

[

]

[ ]

Eqn. 11-1

$$h_{gap} = M_{gap\,gas} * h_{gap\,gas} + h_{rad} + h_{contact}$$

where

h_{gap} = the total gap conductance,

$M_{gap\,gas}$ = the gap gas conductance multiplier,

$h_{gap\,gas}$ = the gap gas conductance,

h_{rad} = the gap radiation conductance, and

$h_{contact}$ = the gap contact conductance.

[ ]

[ ]

Eqn. 11-2

$$h_{gap\,gas} = \frac{k_{gas}}{8} * \sum_{n=1,8} 1/\left[\tau_{gap\,n} + 3.6(R_F + R_C) + (g_1 + g_2)\right]$$

where:

k_{gas} = composite gas thermal conductivity

$\tau_{gap\,n}$ = nominal gap width specified at 8 separate angles over the entire gap where the extremes vary between the soft contact between the cladding and fuel pellet to double the gap size

R_F = fuel pellet surface roughness

R_C = clad inside surface roughness

$(g_1 + g_2)$ = temperature jump distance

[ ]

[ ]

Eqn. 11-3

$$h_{contact} = \frac{0.1565\, k_h}{R_{eff}} * M_{2h} * \left(\frac{P_{contact}}{H_m}\right)^{0.5} * max\{1, \left(\frac{P_{contact}}{6.89E6}\right)^{0.5}\}$$

where

[ ]

Eqn. 11-4

$$k_h = \frac{2\, k_f\, k_c}{(k_f + k_c)}$$

[ ]

Eqn. 11-5

$$R_{eff} = \sqrt{{R_F}^2 + {R_C}^2}$$

[

]

Eqn. 11-6

$$M_{2h} = 29.28 * (R_F)^{0.528}$$

[

]

Detailed Response Part b:

[ ]

Table 11—1 BOL UO_2 PCT Results

[ ]

Table 11—2 MOL UO_2 PCT Results

[ ]

Table 11—3 EOL UO_2 PCT Results

[ ]

Table 11—4 MOL 2wt% Gadolinia PCT Results

Table 11—5 MOL 8wt% Gadolinia PCT Results

[ ]

Figure 11—1 2.506-ft BOL UO_2 HP Gap Gas Mult. Ruptured Node Temperature Comparison Plots

Figure 11—2 2.506-ft BOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Temperature Comparison

Figure 11—3 2.506-ft BOL UO_2 HP Gap Gas Mult. Ruptured Node Gap Conduction Comparison

Figure 11—4 2.506-ft BOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Gap Conduction Comparison

Figure 11—5 2.506-ft BOL UO_2 HP Gap Gas Mult. Fuel-Clad Gap Thickness Comparison

Figure 11—6 2.506-ft MOL UO_2 HP Gap Gas Mult. Ruptured Node Temperature Comparison

Figure 11—7 2.506-ft MOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Temperature Comparison

Figure 11—8 2.506-ft MOL UO_2 HP Gap Gas Mult. Ruptured Node Gap Conduction Comparison

Figure 11—9 2.506-ft MOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Gap Conduction Comparison

Figure 11—10 2.506-ft MOL UO_2 HP Gap Gas Mult. Fuel-Clad Gap Thickness Comparison

Figure 11—11 2.506-ft EOL UO_2 HP Gap Gas Mult. Ruptured Node Temperature Comparison

Figure 11—12 2.506-ft EOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Temperature Comparison

Figure 11—13 2.506-ft EOL UO_2 HP Gap Gas Mult. Ruptured Node Gap Conduction Comparison

Figure 11—14 2.506-ft EOL UO_2 HP Gap Gas Mult. Peak Unruptured Node Gap Conduction Comparison

Figure 11—15 2.506-ft EOL UO_2 HP Gap Gas Mult. Fuel-Clad Gap Thickness Comparison

Figure 11—16 2.506-ft MOL 2wt% Gad HP Gap Gas Mult. Ruptured Node Temperature Comparison

Figure 11—17 2.506-ft MOL 2wt% Gad HP Gap Gas Mult. Peak Unruptured Node Temperature Comparison

Figure 11—18 2.506-ft MOL 2wt% Gad HP Gap Gas Mult. Ruptured Node Gap Conduction Comparison

Figure 11—19 2.506-ft MOL 2wt% Gad HP Gap Gas Mult. Peak Unruptured Node Gap Conduction Comparison

Figure 11—20 2.506-ft MOL 2wt% Gad HP Gap Gas Mult. Fuel-Clad Gap Thickness Comparison

Figure 11—21 2.506-ft MOL 8wt% Gad HP Gap Gas Mult. Ruptured Node Temperature Comparison

Figure 11—22 2.506-ft MOL 8wt% Gad HP Gap Gas Mult. Peak Unruptured Node Temperature Comparison

Figure 11—23 2.506-ft MOL 8wt% Gad HP Gap Gas Mult. Peak Ruptured Node Gap Conduction Comparison

Figure 11—24 2.506-ft MOL 8wt% Gad HP Gap Gas Mult. Peak Unruptured Node Gap Conduction Comparison

Figure 11—25 2.506-ft MOL 8wt% Gad HP Gap Gas Mult. Fuel-Clad Gap Thickness Comparison

12.0 RAI 12

Question:

AREVA asserts in the middle of the first paragraph on page 4-14 of Reference R-1 that "while [ ] can change the heat removal during the first several seconds of the LOCA, it is a minimal effect and the variation is acceptable." Provide addition clarification to show the effect is minimal and the variation is acceptable.

Response:

The [ ] the total gap conductance terms in RELAP5 as computed based on the equations given in RAI-11a. Once the contact conduction is lost, which is within the first two seconds of the limiting double-ended guillotine LBLOCA transient (Figure 11—8 and Figure 11—9), the [ ] terms in the contact conduction equation are no longer used. Thereafter, only the gas conductance is minimally affected because the gap size rapidly increases and it dominates the denominator from Eqn. 11-2 during the transient, [ ] The fuel and cladding gap sizes and temperature plots of the LBLOCA cases performed to respond to RAI-11 are used to confirm information discussed in this RAI as well.

[

] This is shown by comparing the fuel and cladding temperatures for UO_2 fuel at BOL (Figure 11—1 and Figure 11—2), MOL (Figure 11—6 and Figure 11—7), 2wt% gadolinia fuel at MOL (Figure 11—16 and Figure 11—17) and 8wt% gadolinia fuel at MOL (Figure 11—21 and Figure 11—22). As can be seen in these figures, the fuel and cladding temperatures are very similar in all cases for the first 5 seconds.

The lower power EOL UO_2 fuel pin temperatures (Figure 11—11 and Figure 11—12) started to show some variations starting at 3 seconds, but as provided in RAI 11 the EOL PCT for all cases are more than [ ] below the PCTs at MOL. Therefore, the earlier changes in temperatures and larger variations in PCTs due to gap gas multiplier changes are not of consequence as they do not set any limits.

What is clear from these results is that after the first few seconds of the LBLOCA, the gap conductance calculations are based on an expanded gap size as shown in Figure 12—1, which is the ruptured segment from Figure 11—5 shown on an adjusted gap size and time scale. Once the gap grows to more than 50 microns (1.64×10^{-4} ft) the [ ] have little to no effect on in subsequent calculations. If there is fuel-clad contact at steady state it is lost in the first few seconds as the gap size increases due to fuel contraction and cladding expansion. The gap gas multiplier that was adjusted at the onset of the problem based on [ ] to match the input VAFT supplied did not alter the early blowdown fuel pin thermal response. Later during the transient, the variations in gap gas multiplier have some effect on the total gap conductance. These conduction differences for gap gas multiplier ranges between [

]

Figure 12—1 Hot Pin, Hot Spot Gap Size

13.0 RAI 13

Question:

Provide additional description of the adjustment process, including the as-adjusted fuel rod parameters, analogous to the information provided in Tables 5-7 and 7-5 of Audit Document 32-9245587-000, "LBLOCA Demonstration Analyses for TCD."

Executive Summary:

The steady-state fuel pin modeling used in RELAP5 imposes 95/95 VAFTs, fuel pin dimensions, and gap gas properties from a fuel performance code. The problem is over-specified as RELAP5 performs its own gap conductance calculation. Therefore, the over-specification is managed by introduction of a gap gas multiplier on the gas conductance term shown in Eqn. 11-1. The implementation of the large VAFT increases to account for TCD caused the calculated gap gas multipliers to deviate substantially from a value of [ ] and this can impact the transient heat removal and overall PCT prediction. The results of studies presented in RAI 11 showed that the PCT changes were minimal when the hot spot gap gas multipliers were in the range of [ ] Adjustment of the [ ] is used to achieving gap gas multipliers near [ ]

[ ]

Detailed Response:

Eqn. 13-1

Table 13—1 [

]

Figure 13—1 [ ]

Figure 13—2 [ ]

Figure 13—3 [ ]

Figure 13—4 [ ]

Figure 13—5 [ ]

Figure 13—6 [ ]

Figure 13—7 [ ]

Figure 13—8 [ ]

14.0 RAI 14

Question:

AREVA mentioned during the audit that the [

] in the hot rods modeled in the core region. The following additional information is requested to clarify the consequence of monitoring only three nodes.

a. In many cases the PCT occurs downstream from the hot cell (the peak power location). Confirm that the PCT is predicted [

] in the LBLOCA analysis.

b. It appears that the gap multipliers are [

]

c. Clarify the process of determining and monitoring the gap gas multipliers for the hot bundle and the average bundle.

Response:

Part a:

The location of the PCT frequently occurs in the peak power location or within one node above or below this location for the 177-FA LL plants, particularly if the PCT occurs in a ruptured node. However, the methodology does not force the PCT location to be in one of the three nodes spanning the peak power location. 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. A PCT outside this zone is more likely to occur with core inlet or exit skewed axial peaks.

The rod locations where PCT is typically predicted (ruptured versus limiting unruptured) is similar to those targeted for the gap gas multiplier, but not necessarily identical. While iterations are performed to achieve a gap gas multiplier value of [ ] near the peak power location, the PCT may occur slightly outside this zone. Since the gap gas multiplier adjustments are performed before the case is analyzed, it is prudent to focus on the peak power location when developing the analysis input. In all cases, the gap gas multiplier at the PCT location will be reported. 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. Therefore, rather than change the methodology to force a PCT location, the method used will assure the PCT is predicted with an appropriate gap gas multiplier.

Although not explicitly part of the RAI, the gap gas multipliers for the gadolinia fuel hot pins will be adjusted similarly as those for the UO_2 hot pins. The gap gas multiplier at the location of the gadolinia PCT will be checked to ensure they fall within the range from [ ] Like the UO_2 hot rods, reanalysis with adjusted [ ] to achieve gap gas multipliers in the targeted range will be performed if they were not within this range.

Part b:

As described in the responses to RAI 12, the RELAP5 gap gas multiplier varies axially along the length of the fuel rod as the gap gas multiplier is adjusted locally at steady-state to obtain the gap conduction that achieves the 95/95 VAFT while the over-specification radii account for geometrical changes from fuel density irradiation variations and cladding creep. The local power, local burnup, local fluid temperatures, temperature difference across the gap, fuel-clad contact pressure, and other relationships influence what gap gas multiplier is needed to achieve the targeted VAFT at each location. Two MOL cases previously presented in RAI 11 that examine the effects of gap gas multipliers ranging from [ ] will be used to answer this RAI.

Figure 14—1 shows the gap gas multiplier versus elevation for two MOL 2.506-ft core inlet power peak cases. One hot pin has a hot spot gap gas multiplier of [ ] (first curve from Figure 13—7) and one hot pin has a hot spot gap gas multiplier of [ ] These two hot pins have considerable differences in gap gas multipliers up and down the rod but still had similar overall PCTs of [ ] multipliers respectively (see unruptured PCTs from RAI 11, Table 11—2).

While larger variations in multipliers changed the overall PCT by only [ ] additional evidence is provided of the how the local gap gas multipliers change the maximum cladding temperatures axially along the rod. Figure 14—2 shows the highest cladding temperatures at each elevation along the rod for both the [ ] multiplier cases. This figure confirms that there are minimal changes in the maximum cladding temperatures over the entire rod. The largest difference was observed at the 2.506-ft elevation, which happens to be the ruptured segment for both cases. The timing of rupture and the expanded cladding dimensions are similar but different enough to produce the variations in ruptured node PCT shown in the figure and listed in Table 11—2.

The similarity of the PCT comparisons and the local maximum cladding temperatures confirm that multiplier changes that vary by roughly [ ] between the two cases do not produce a significant difference in key results. In some of the lower power regions the multipliers were above [ ] ; however, the local maximum cladding temperatures were effectively unchanged and will not lead to substantial changes in the over PCT. Therefore, the multipliers away from the peak power location do not need to be explicitly checked.

Part c:

The [ ] variables are used to adjust the gap gas multipliers to the targeted range between [ ] for the hot bundle and the average channel at the axial peak power or hot spot location using a similar approach as that developed for the hot pin. A BOL sensitivity study was performed to investigate the impact of different gas gap gas multipliers for the hot bundle. The case with the hot pin multiplier of [

] when the hot bundle multipliers were vastly different. These PCT differences are within the calculation accuracy of the method plus the hot bundle will not set the limiting PCTs. Therefore, reanalysis is not required if the gap gas multiplier at the hot bundle PCT locations do not fall within the range of [ ] The hot bundle sets the fluid conditions for the hot pin and large variations in the hot bundle multipliers did not effectively change the overall PCT.

The average channel maximum cladding temperatures are much lower due to the lower power levels and separation from the hot bundle. The net result is that large changes in average channel gap gas multipliers will not appreciably change the overall PCT. Therefore, while the multiplier will be adjusted to be within the range for future LBLOCA analyses, no specific checking of the multiplier or reanalysis is needed if the gap gas multiplier at the average channel PCT location does not fall between [ ]

Figure 14—1 [ ]

Figure 14—2 MOL 2.506-ft UO_2 Hot Pin Maximum Cladding Temperature versus Fuel Rod Elevation

15.0 RAI 15

Question:

Uncertainties are added to the VAFTs predicted by TACO3/GDTACO for the hot pin and hot bundles. Provide the following additional information.

a. Detailed discussions of the development and qualification of the uncertainties. In particular, the discussion should highlight the application of uncertainties in the modified LOCA methodology that deviates from the previously approved methodology.

b. Justification for the uncertainty factor of [ ] The uncertainty factor of [ ] determined for the UO_2 hot pin, was based on a statistical analysis of measurements versus TACO3 predictions. However the same uncertainty factor is also applied to temperatures of Gadolinia hot pins (see Equation 6).

Response:

Part a:

As discussed in Section 3.1.1.2 of the TCD Supplement (Reference 1), the BOL range (e.g. burnups less than or equal to 1 GWd/mtU) UO_2 hot pin or hot bundle uncertainties are based on TACO3 and they are unchanged with the TCD Supplement. The approved 95/95 uncertainty for TACO3 fuel temperature predictions is [ ] in BAW-10162PA-00 (Reference 5, p. I-10). This uncertainty was based on a statistical analysis of the measured to predicted data. The BOL gadolinia hot pin uncertainties are based on GDTACO and they are also unchanged. The approved 95/95 uncertainty for GDTACO fuel temperature predictions is [ ] in Reference 6 (p. 4-1).

The primary change in the modified LOCA methodology is the application of the TCD bias function to the UO_2 hot rods for TIL applications. For burnups greater than or equal to 10 GWd/mtU, the NRC approved method described in BAW-10164PA, pages 5-537 through 5-539 (Reference 4) is changed to include the TCD bias factor in the initial fuel temperature uncertainties. In the modified LOCA methodology a fuel temperature uncertainty of [ ] is applied to the best-estimate hot pin VAFT from TACO3 and the burnup-dependent generic UO_2 TCD bias factor (Table 4-1 of Reference 1) is added to obtain the 95/95 VAFT for input to RELAP5 at the hot spot. The uncertainty application change from temperatures in C versus F results in a slightly more conservative uncertainty that was included in the development of the TCD bias function. The VAFTs in locations away from the hot spot are calculated as described in the response to RAI 6.

For burnups greater than or equal to 10 GWd/mtU the hot spot VAFT is increased by an uncertainty of [ ] on the best-estimate gadolinia hot pin VAFT from GDTACO and the burnup-dependent generic gadolinia TCD bias factor (Table 4-2 of Reference 1) added. The uncertainty application change from temperatures in C to F results in a slightly more conservative uncertainty that was included in the development of the gadolinia TCD bias function. The gadolinia VAFTs in locations away from the hot spot are calculated as described in the response to RAI 6.

In the unlikely event that LBLOCA analyses are needed for burnups between 1 and 10 GWd/mtU, linear interpolation based on burnup is performed. The BOL VAFT temperatures with its uncertainty and the TIL VAFT temperatures with their uncertainty are developed at 1 GWd/mtU. The hot spot TCD adjusted VAFT with its uncertainty and 10 GWd/mtU TCD bias factor are developed at 10 GWd/mtU. A linear interpolation based on burnup is used for the hot spot as described in Section 4.1 of the TCD Supplement (Reference 1). The rod elevations away from the hot spot will be set by the approach described in RAI 6.

The hot bundle uncertainty for the BOL burnup range remains at [ ] The TIL hot bundle uncertainty for burnups greater than [ ] as described in Section 4.1 of the TCD Supplement (Reference 1). Interpolation based on burnup is used between 1 and 10 GWd/mtU.

No uncertainty is used for the average channel, which is modeled at BOL. The average channel uncertainty approach is unchanged from what was approved by the NRC as shown on page 5-537 to 539 of the BAW-10164PA (Reference 4).

Although not directly applied in the modified LOCA methodology when the generic TCD bias is used, the 95/95 uncertainty for COPERNIC2 fuel temperature predictions was used in the development of the TCD bias functions. For LOCA applications, the approved 95/95 fuel temperature uncertainty is [ ] as defined in Reference 7 (p. 12-5). This uncertainty was developed through a statistical analysis of the measured and predicted fuel temperatures in the Response to RAI 3 of Reference 7 (Appendix A p. 14-9).

Part b:

The approved 95/95 uncertainty for GDTACO fuel temperature predictions is [ ] in Reference 6 (p. 4-1). This uncertainty is used for the entire rod for BOL applications (burnups less than or equal to 1 GWd/mtU). For TIL applications greater than to equal to 10 GWd/mtU, the modified LOCA initialization methodology applies an [ ] fuel temperature uncertainty to degrees Fahrenheit to the hot spot and adds the generic gadolinia TCD bias function to the best-estimate hot pin VAFT from GDTACO. The unit change from C to F results in a slightly more conservative penalty and was made for consistency with the TCD bias function. For burnups between 1 and 10 GWd/mtU a linear interpolation for the gadolinia hot pin hot spot uncertainty is performed similar to what was described for UO_2 fuel in Part a of this RAI response.

16.0 RAI 16

Question:

A couple of labels in the figures of Reference R-1 are ambiguous and may lead to wrong interpretations. One example is "RELAP w/o TCD" in Figures 4-4 and 4-5. This represents the RELAP5 initial temperature with TCD bias but without considering the burnup-dependent fuel thermal conductivity. Clarify the labels of "RELAP w/o TCD" and "RELAP-TCD" with appropriate discussions.

Response:

Figure 4-4 of the TCD Supplement (Reference 1) shows two separate sets of mesh point temperatures for an MOL case that calculates the temperature profile using a BOL fuel thermal conductivity model. One set of temperatures is from the TACO3 best-estimate fuel pellet initialization. Since TACO3 uses unirradiated (e.g. no TCD) fuel thermal conductivity at all TILs, the temperature distribution (labeled TACO BE) is based on a BOL fuel thermal conductivity. The other set of temperatures is from the RELAP5 initialization. The RELAP5 temperature distribution (RELAP w/o TCD) is also based on a BOL fuel thermal conductivity. The VAFT targeted for RELAP5 is the TACO3 BE VAFT with the 95/95 uncertainty plus the MOL generic TCD bias function increase. The RELAP5 code used a BOL thermal conductivity to determine the temperature distribution that matches the generic TCD-biased VAFT. These items will be clarified by changing the figure title to "MOL LOCA Initialization Using BOL Fuel Thermal Conductivities to Determine the Fuel Radial Temperature Distributions." In addition, the second legend label will be changed to "RELAP5 95/95 with Generic TCD Bias Factor." The revised Figure 4-4 is presented in the markup section at the end of this document. The revised figures will be included in the approved version of the topical report.

Figure 4-5 of the TCD Supplement (Reference 1) shows the same two curves ("TACO BE" and "RELAP –w/o TCD" in the TCD Supplement). The new labels described above should be used with one change. The label for the RELAP curve was expanded to "RELAP5 95/95 with Generic TCD Bias Factor for BOL Fuel Thermal Conductivity" to capture the proper thermal conductivity used. Figure 4-5 also adds two additional curves. The first curve added is the COPERNIC2 best-estimate temperature ("COPERNIC BE" in the TCD Supplement), which uses burnup dependent fuel thermal conductivities. This BE temperature does not have the [ ] applied to produce a 95/95 uncertainty adjusted VAFT that is used as input for the LOCA analysis. The second curve added ("RELAP – TCD" in the TCD Supplement) achieves the 95/95 COPERNIC2 VAFT using the TCD adjusted fuel thermal conductivity at [ ] from Figure 4-6 of the TCD Supplement (Reference 1) in RELAP5 to calculate the temperature distribution shown. The second curve will be retitled "RELAP w 95/95 Generic TCD Bias for MOL Fuel Thermal Conductivity." A markup of Figure 4-5 is provided in the markup section at the end of this document. The revised figure will be included in the approved version of the topical report.

17.0 RAI 17

Question:

The last sentence of the second paragraph on page 4-9 states that the shifts (of the mesh point temperatures) are most obvious at the fuel and clad interface and the outside clad radius. However, there is no clad temperature difference between the predictions of COPERNIC2 and TACO3 as shown in Figure 4-5. Clarify the difference between the discussion and Figure 4-5.

Response:

The RAI added in the parenthetical phase "(of the mesh point temperatures)" but the word "shifts" in the TCD Supplement text was focused on radial mesh point location and not on temperature. The last sentence of the second paragraph on page 4-9 of the TCD Supplement (Reference 1) would be clearer if written as, "The radial dimension shifts are most obvious at the fuel and clad interface and the outside clad radius."

The temperature distribution through the cladding is similar for all codes. The fluid temperature (shown arbitrarily at the 0.019 ft radius) is similar for all codes. The forced convection surface heat transfer models are similar as is the LHR. Therefore the cladding temperatures are similar for all codes independent of the fuel TCD changes. The key temperature differences begin to show up across the gap (e.g. at the fuel and cladding interface). The shift that is alluded to in the text is a shift in radius not temperature as this interface is shown at different radii. The dimensions for RELAP5 are cold unexpanded while TACO3 and COPERNIC2 are hot expanded valves. The step change in temperature difference at the interface between the fuel and cladding is the key parameter as it is used for the gap conduction terms and gap gas multipliers. It is also noted that the outside radius of the cladding from COPERNIC2 is larger than those from RELAP5.

18.0 RAI 18

Question:

Section 5 of Reference R-1 shows the changes in the PCT predictions with and without TCD adjustments. In all cases a core inlet skewed axial peak at 2.506 ft was taken into account. The second paragraph on page 5-3 of the LTR states, "This core inlet elevation was selected because this is the elevation at which LOCA analyses set the core imbalance limits." 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.

Response:

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. The core power distribution analyses use control rod insertion and variations in steady-state and transient xenon to establish limiting skewed peaks within the core. These best-estimate peaks are augmented and then compared to the LOCA LHR limits. Insertion of control rods can push power to the bottom of the core for a core inlet power peak. Insertion and subsequent withdrawal of rods when peak xenon builds up at the core inlet pushes the peaks to extremes at the core exit. It is difficult to create high peaking in the center of the core. The comparison of the core peaking with augmentation to the LOCA LHRs show that the minimum peaking margins are at the bottom or top of the core. A picture of typical LOCA peaking margin versus offset is shown in Figure 1-4 of BAW-10192, Volume III (Reference 10, p. LA 89). In this plot negative offsets are peaks at the core inlet and positive offsets are peaks at the core exit. Based on this understanding, the core inlet is typically limited by LOCA LHR limits, but the core exit is the next most limiting, with more than 15 percent margin at BOL. Typically, non-LOCA departure from nucleate boiling (DNB) sets the core exit LHR limits.

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.

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.

19.0 RAI 19

Question:

Supplement the information presented in Tables 5-1 through 5-4 of Reference R-1 by including the peak rod burnup and the TACO3/GDTACO best-estimate initial peak VAFT as determined using the [ ] LOCA initialization.

Response:

The rod local burnup at the peak power location and the maximum burnup along the rod are shown in the revised tables along with the TACO3 best-estimate VAFTs requested.

A markup of Tables 5-1 through 5-4 is provided in the markup section at the end of this document. The revised tables will be included in the approved version of the topical report.

Columns in Tables 5-1 through 5-4 will have acronyms for the following:

Original EM Analyses = OEA

Supplement with TCD Compensation = S+TCD

Supplement with TCD Compensation & Reduced LHR = S+TCD+RLHR

20.0 RAI 20

Question:

In Section 3.2.2 of Reference R-1 a comparison of temperatures between calculated and measured data from high burnup test rods is used to validate the generic TCD bias functions. Equation 7 shown on p. 3-12 of Reference R-1 [ ] There is no technical basis provided in the TR to justify the equality shown in the equation. However it can be inferred from Equation 3 and the discussion in the first paragraph on Page 4-5 of Reference R-1 that if the [ ] is removed from the right hand side of Equation 7 the resulting temperature then represents a best-estimate prediction of centerline temperature that accounts for TCD. That is,

[ ]

Using the above formulation as the predicted centerline temperature, quantify the temperature difference (the predicted minus measured centerline temperature) that bounds 95% of the data with a 95% confidence level. That is, find the value of X, such that

[ ]

Response:

The temperature difference (measured centerline temperature minus best estimate TACO3-TCD prediction that accounts for TCD) that bounds 95% of the population with 95% confidence is [ ]

The quantification of the temperature difference (measured centerline temperature minus "best-estimate" TACO3-TCD predicted centerline temperature) data is shown below in Figure 20—1.

The mean temperature difference is [ ]

Using the Owen K factor (Reference 13) of [ ]

It should be noted that the histogram shows that the data is not a normal distribution and thus the Owen factor is not strictly applicable. However using order statistics, this method is shown to be conservative.

To evaluate the 95/95 limit using order statistics, the data sample was sorted in descending order of (measured centerline temperature minus best-estimate TACO3-TCD predicted centerline temperature). There are [ ] data points in the sample. Reference 14 defines the degree of confidence, g, associated with the fractional probability, P that values chosen at random from a population will fall below the mth largest value. This degree of confidence, g, is defined in terms of the incomplete beta function, I; for tabulated values of g, the following inequality applies:

Eqn. 20-1

$$g \leq I_{1-P}(m, n - m + 1) = 100$$

For n equal to [ ] data points and a g corresponding to 95% confidence at the 95% probability level, m is found by interpolation of the values in Table I of Reference 14 to be [ ] largest (measured minus predicted) value is [ ] Hence using ordered statistics with 95% confidence at least 95% of the population of (measured - predicted) values will be less than [ ] Therefore, the value of [ ] calculated under the assumption of normally distributed data is conservative.

The calculated uncertainties are less than the value of [ ] used in TCD Supplement (Reference 1) and thus the methods employed by TCD Supplement are conservative.

Figure 20—1 Histogram and Cumulative % for Measured Data Comparison

21.0 RAI 21

Question:

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 and the clad inner radius. The LOCA EM applies RELAP5 calculated radial displacement factors for the fuel pellet and the clad to set the fuel radius and the clad inside radius for the gap size calculation throughout the transient (see discussion on p. 4-7 of Reference R-1). The following information is requested to assist in the review of the application of the displacement factors in the context of accounting for the effect of TCD in a LOCA analysis.

a. The discussion of the radial displacement factor is in Reference R-1, Section 4.2 – LOCA Transient EM Method Changes. Identify and clarify changes in the calculation and application of the radial displacement factors that are different from the approved LOCA EM.

b. Explain if there is any impact on the determination and application of the TCD bias factor due to the application of the radial displacement factors in the LOCA initialization.

c. Is there any difference in the calculation of the radial displacement factor and its axial variation for all the different fuel in the core (hot pins, hot bundle and average bundle)?

d. How does the application of the radial displacement factors affect the determination of the gap gas multipliers?

e. Provide justification for using constant radial displacement factors throughout the LOCA transient.

Response:

Part a:

The approach used to specify the hot fuel pin geometry parameters in RELAP5 based on the steady-state fuel pin code for TCD applications is unchanged from the approved EM. The RELAP5 fuel and cladding radii are set via input at each location to exactly match the geometry from the steady-state fuel pin code that includes normal operation irradiation induced geometrical changes.

The fuel pin parameters from the steady-state fuel pin code (i.e., TACO3, GDTACO and/or COPERNIC2) are provided as an initial value input to the RELAP5 EM pin model for use in the LOCA analysis. The steady-state fuel pin code calculates the pin geometry based on the thermal characteristics along with fuel density and cladding strains that change with burnup. These geometrical and thermal input are provided to RELAP5 as well as the pin pressure, gas composition, and 95/95 VAFT for the hot pin and hot bundle. The average channel is supplied with the same parameters and the best-estimate VAFT for this channel.

The RELAP5 heat structure geometry used in the conduction solution is based on cold, unstressed, fuel pin geometry parameters. The conduction solution includes fixed dimensions for the fuel pin, including the gap. However, RELAP5 calculates the total gap conductance based on the dynamic gap dimensions that change during the LOCA transient. RELAP5 calculates fuel thermal expansion, cladding thermal expansion, and elastic as well as plastic or rupture cladding strains. The total conduction based on the dynamic gap size calculated by RELAP5 is converted back into an effective thermal conductivity based on the cold gap size for the conduction solution.

During steady-state initializations, RELAP5 calculates its own dynamic geometry that is the cold geometry altered only by thermal expansion of the fuel and the cladding and elastic strain from the cladding hoop stresses. The difference between the RELAP5 and TACO3 fuel pin outside radius at each axial level, is the fuel over-specification term or fuel radial displacement factor. This term is effectively the irradiation fuel density changes plus any thermal expansion differences from VAFT uncertainties applied to RELAP5.

The RELAP5 cladding over-specification term, or cladding radial displacement factor, is effectively the cladding irradiation and creep strain contributions used in the steady-state fuel pin code but not in RELAP5. This approach used for both the fuel and cladding incorporates the irradiation and cladding creep into the LOCA application without having to include these time in life models that mimic the fuel pin irradiation changes that occur over 6 to 8 years of normal operation. These geometrical changes become an input to the RELAP5 code that is designed to calculate thermal hydraulic analysis of a LOCA, whose transient period of interest is in the order of minutes to hours versus years.

At BOL, there is effectively no irradiation, and the fuel density is effectively the nominal, as-manufactured density. RELAP5 uses the 95/95 VAFT thermal expansion for the hot pin where the best-estimate VAFT thermal expansion is calculated by the steady-state fuel pin code. Figure 21—1 shows the difference between RELAP5 and TACO3 fuel outside radii for the hot UO_2 rod at BOL steady state conditions. At BOL, the primary difference between the fuel pellet radii between TACO3 and RELAP5 is created by the VAFT uncertainty used in RELAP5. The fuel radial displacement factor (Equation 2.3.2-55 of Reference 4) is unique at each axial level. At BOL, they are all negative for the hot pin because of the VAFT uncertainty.

During plant operation, the fuel irradiation increases. During the first few hundred MWd/mtU of operation, there are dimensional changes that include an initial fuel densification. After achieving the maximum densification, additional accumulated irradiation causes pores and cracks to form in the fuel pellet matrix and the net fuel density decreases. At higher burnups, the fuel density and thermal expansion changes become more substantial. The change in the fuel radius from the steady-state fuel pin code captures these effects while RELAP5 does not.

Using the steady-state fuel code geometry effectively captures the normal operation TIL effects via the fuel radius radial displacement factor. Because the burnup varies over the length of the rod in the steady-state fuel pin code, the relative differences in fuel geometries between the fuel pin code and RELAP5 vary axially as well. Figure 21—2 shows these steady-state differences for the fuel outer radius at MOL for the hot pin with a rod average burnup of [ ] RELAP5 uses a 95/95 VAFT uncertainty and predicts a shape similar to that for BOL, but the steady-state fuel pin code has the fuel swelling included in its radii with no VAFT uncertainty. The net result is that the fuel radial displacement factors can be negative or positive after BOL. It changes based on local burnup in the core that varies with elevation due to the normal core power distribution.

The steady-state fuel pin code calculation of hot, expanded cladding inside radius is based on the aggregate effect of creep, irradiation, thermal expansion, and elastic hoop strain. At BOL there is little irradiation and creep. Since the pin pressure is supplied to RELAP5, the elastic hoop strains are also similar. Therefore, the only differences between the steady-state fuel code and RELAP5 are the code modeling variations, any thermal differences related to fluid temperature variations, and variations in the cladding surface heat transfer correlations. These variations in the inside cladding radius are small at BOL, as shown in Figure 21—3. The BOL variations in the two inside cladding radii at steady state prior to the transient onset are accounted for by the cladding radial displacement factor (Equation 2.3.2-56 of Reference 4). When the fuel and cladding radial displacement factors are both applied in RELAP5, the dynamic gap size from the steady-state code is identical to that in RELAP5 just prior to initiation of the LOCA transient. Figure 21—5 shows the BOL radii that establish the dynamic gap size at BOL.

With increasing burnup, the cladding creep and elastic strains overwhelm the thermal and irradiation stains such that the inside cladding radius decreases. The cladding contraction and fuel expansion from burnup related swelling cause the dynamic gap size to decrease and the two surfaces come into hard contact. With increased irradiation, the fuel-clad contact pressure grows. When the fuel-clad contact pressure plus internal pressure exceed the system pressure, the elastic stain changes direction and causes the cladding to expand outward. Since the fuel-clad contact varies axially over the length of the rod. The cladding radius is smaller away from the high power middle regions because there is less fuel expansion due to the lower power that reduces irradiation and thermal expansion. Figure 21—4 shows the TACO3 steady-state initial geometry of the hot pin cladding inside radius at MOL. It also shows the RELAP5 radii that do not model normal irradiation creepdown or hard contact expansion effects. Since RELAP5 does not model the cladding creepdown, the cladding radial displacement factor is negative.

Demonstration of the changes in the fuel and cladding dimensions controlling the gap size with burnup can be derived by comparing curves from Figure 21—1 through Figure 21—4. The steady-state dimensions controlling the burnup-dependent gap size from the TACO3 code are shown in Figure 21—5 for BOL conditions. These BOL radii were combined with MOL and EOL burnup-dependent initial dimensions in Figure 21—6 to depict the steady-state fuel pin code gap size changes at three different TILs. This figure shows the fuel radius expansion from the fuel density decreases at BOL as porosity increases inside the pellet at MOL and EOL. The downward cladding creep is also evident at the top and bottom of the rod when BOL to MOL conditions are compared. It can also be seen that the fuel-clad contact controls the dimensions at the higher power central regions of the rod at MOL. Continued expansion of the fuel between MOL and EOL pushes the cladding outward, and this effect is captured directly by the steady-state fuel pin code. RELAP5 captures these effects via the input dimensions and the use of the fuel and cladding radial displacement factors to achieve these burnup dependent geometrical parameters.

This discussion describes the approach used to establish the RELAP5 radial fuel and cladding displacement input and demonstrate how TIL changes to the fuel and cladding are used as input to the LOCA analyses. The approach used is identical with or without TCD and therefore the approach used is unchanged in the TCD supplement. This approach achieves the burnup-dependent geometrical effects from fuel densification or cladding creep and irradiation effects from normal plant operation without having to incorporate similar models into the RELAP5 code. During the short duration of the LOCA transient, the fuel densification or cladding creep and irradiation components do not have time to evolve so they are held constant in RELAP5 via the fuel and cladding radial displacement applications. These terms are used along with transient thermal expansion effects as altered by the cladding elastic, plastic, and rupture strains that response to changes in the rod temperature, internal rod pressure, and RCS pressure.

Part b:

The TCD bias factor was developed by direct comparison between two steady-state fuel pin codes and is used to ensure a conservative prediction of the initial VAFT. The radial displacement factors are used only in RELAP5. As described above (in Part a), these factors are used by RELAP5 to implicitly capture geometric effects including fuel densification initially followed by void induced swelling and cladding creep calculated by TACO3. TACO3 also calculates the thermal expansion effects of the fuel and the thermal and elastic expansion effects of the cladding. The process of determining the radial displacement factors is the same with or without TCD considerations.

If TACO3 included a degraded thermal conductivity model, the fuel temperatures would be higher and the thermal expansion of the fuel would be slightly larger. Since TCD builds in with burnup, the TCD related VAFT increase would increase the fuel thermal expansion with burnup. The impact is limited, however, because once fuel-clad contact occurs, there is effectively a constant difference between the fuel and cladding dimensions that does not change as the burnup continues to increase. The fuel and cladding radii at MOL and EOL from Figure 21—6 show this. Both the fuel and cladding radial displacement factors would increase by similar values, but the net gap size will not change. During the transient the net change in the gap size is the critical parameter for fuel stored energy removal and the gap size would not changes. Therefore, the burnups when the TCD effects would be most noticeable is at the irradiation that is just prior to the onset of fuel cladding contact. Generally, this is a burnup where the VAFT is low, which will result in a non-limiting PCT and is therefore not typically analyzed. The two burnups that are potentially most limiting in terms of PCT are either at BOL or MOL. At BOL, there are no TCD related thermal expansion effects. At MOL, there is considerable fuel-cladding contact, so the net gap size calculations would not be affected by the fuel performance code fuel radius that ultimately sets or controls the radial displacement factors used in RELAP5.

Part c:

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 hot bundle has a lower 95/95 VAFT uncertainty than the UO_2 hot pin but uses the same geometry; thus the initial fuel pin geometry determined by the steady-state fuel performance code and imposed on the UO_2 hot pin and hot bundle are identical. The radial displacement factors (aka. over-specification terms) calculated by RELAP5 will be slightly different due to the VAFT uncertainty effect on the thermal expansion differences. The average channel is initialized at BOL for all TIL LOCA analyses, therefore its radial displacement factors will not change for different hot bundle/hot pin TIL analyses. For gadolinia pins, the fuel geometry is established similarly to the UO_2 hot pins and the same initialization methods are performed separately for each gadolinia pin concentration.

Part d:

The radial displacement factors force the RELAP5 calculated gap size just prior to initiation of the LOCA transient to be identical to that of the steady-state fuel pin code. These factors capture the irradiation-dependent dimensions that change with burnup. Therefore, these factors must be used, and when they are imposed, the RELAP5 fuel pin geometry is always the same as the steady-state fuel pin code. These factors set the same dynamic gap size, from which the dynamic gap conductance is computed. The gap gas multipliers are established based on this geometry to achieve the specified VAFT at any location along the rod. So while the factors do not directly determine the gap gas multiplier, they are integral to the process that calculations the gap gas multiplier.

Part e:

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.

Another way to look at these factors is by considering other LOCA break sizes. The radial displacement factor approach is used for all LOCA break size applications. During a small break LOCA (SBLOCA) event, the reactor can remains at power for some time before a low pressure reactor trip is obtained. During this period, the radial displacement factors are needed to keep the fuel pin thermal equilibrium from changing unrealistically. As the break size is increased, the length of time that the thermal equilibrium is maintained decreases. However, the fuel density and cladding creep still need to be included in the gap size determination for the fuel pin heat removal. An LBLOCA transient rapidly alters the fuel pin surface heat transfer such that the use of the radial displacement factors may become insignificant, however, the fuel density and cladding creep geometrical changes should still be retained, and they are effectively included via in the cladding radial displacement factor. By keeping the radial displacement factors constant during the transient, they ensure the fuel pin geometry based on fuel irradiated geometry and cladding with its initial creep are appropriately retained in the short duration transient. Any dimensional changes due to thermal effects or elastic effects are applied to the geometry captured by the radial displacement factors. Once the cladding becomes plastic, the clad radial displacement factors are no longer used.

Figure 21—1 BOL Hot Pin Fuel Outside Radii

Figure 21—2 MOL Hot Pin Fuel Outside Radii

Figure 21—3 BOL Hot Pin Inside Cladding Radii

Figure 21—4 MOL Hot Pin Inside Cladding Radii

Figure 21—5 TACO3 BOL Hot Pin Fuel Outside and Cladding Inside Radius

Figure 21—6 TACO3 Hot Pin Fuel Outside and Cladding Inside Radius at BOL, MOL, and EOL

22.0 ADDITIONAL INFORMATION

Equation 8 on page 4-8 of the TCD Supplement describes the total gap conductance, h_{gap}. Equation 9 on page 4-12 gives the total gap gas conduction term $h_{gap\ gas}$ that was a term in Equation 8. In Equation 8 the gap gas thermal conductivity multiplier, $M_{gap\ gas}$, multiplied the $h_{gap\ gas}$ term. However, in Equation 9 $M_{gap\ gas}$ appears again, which when combined with Equation 8 squares the $M_{gap\ gas}$ contribution.

The gap gas multiplier, $M_{gap\ gas}$, should not appear in both equations. Once it is included in Equation 8, it should not be included in Equation 9. A markup of page 4-12 has been prepared to correct this error. The markup is included in the markup section at the end of this report. The revised page will be included in the approved version of the report.

The RELAP5/MOD2-B&W code topical BAW-10164P-A Revision 6 (Reference 4) also has the gap gas multiplier in Equations 2.3.2-2 and 2.3.2-3. It should not be included in the latter equation. The code was checked and it is formulated correctly.

23.0 REFERENCES

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6. BAW-10184PA, Revision 0, "GDTACO Urania – Gadolinia Fuel Pin Thermal Analysis Code," June 1995.
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13. NRC Document SCR-607, "Factors for One-Sided Tolerance Limits and for Variables Sampling Plans." (ML 14031A495)

14. Somerville, Paul N., "Tables for Obtaining Non-parametric Tolerance Limits," The Annals of Mathematical Statistics, Volume 29 , Number 2 (1958), pages 599--601

24.0 NRC REFERENCES FOR RAIS

R-1. AREVA, Inc., "BWNT LOCA: BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants," BAW-10192PA-00, Supplement 1 P/NP, Revision 0, Project No. 728, November 25, 2015, Agencywide Document Access and Management System (ADAMS) Package No. ML 15337A257.

R-2. U.S. NRC, "AREVA Inc. - Babcock and Wilcox Nuclear Technologies Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants - Supplement 1 P to BAW-10192PA- Nuclear Performance and Code Review Branch Audit Report (TAC No. MF7145)," Project No. 728, May 31, 2016, ADAMS Accession No. ML 16147A031 (Proprietary document; no publicly available copy located).

R-3. Babcock and Wilcox Nuclear Technologies, "TACO3 - Fuel Pin Thermal Analysis Code," BAW-10182P-A, October 1989 (Document not found in ADAMS).

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R-5. Framatome ANP, Inc., "COPERNIC Fuel Rod Design Computer Code," BAW-10231 (P/NP)(A), Project No. 728, September 30, 2004, ADAMS Package No. ML042930233.

R-6. AREVA NP, Inc., "Safety Criteria and Methodology for Acceptable Cycle Reload Analyses," BAW-10179(P/NP)(A), Revision 8, Project No. 694, August 6, 2010, ADAMS Package No. ML 102210442.

R-7. AREVA NP, Inc., "RELAP5/MOD2-B&W: An Advanced Computer Program for Light Water Reactor LOCA and Non-LOCA Transient Analysis," BAW-10164P-A, Revision 6, June 2007, ADAMS Accession No, ML091410456 (Proprietary report; no publicly available copy located).

25.0 MARKUP PAGES

TCD Supplement page 3-12

TCD Supplement page 3-21

TCD Supplement page 4-9

TCD Supplement page 4-12

TCD Supplement page 4-23 (Figure 4-4)

TCD Supplement page 4-24 (Figure 4-5)

TCD Supplement pages 5-14 through 5-19 (Tables 5-1 through 5-4). These pages will be renumbered 5-14 through 5-17, which reduces the number of pages for the tables and renumbers the remainder of Section 5. The renumbered pages will be included in the PA version of the report.

[ ]

Equation 7

[ ]

Figure 3-9 and Figure 3-10 plot the ratio of measured fuel temperature to penalized predictions (M/P) for the [ ] test rods benchmarked with TACO3 and GDTACO. The penalties were calculated using Equation 7 with the generic TCD bias functions from Table 3-1 for UO_2 fuel and Table 3-2 for gadolinia fuel. The results show the generic TCD bias functions have adequately penalized the TACO3/GDTACO fuel temperature predictions. Figure 3-11 shows the histogram and cumulative percentage of the M/P values. [

]

3.3 *Generic TCD Bias Range of Application*

There are limitations on the applicability of the generic TCD bias functions. The analyses are focused on the current fuel rod design and operating conditions that are representative of the B&W 177 fuel-assembly (FA) plants.

Table 3-4 Limits of Applicability for Generic TCD Bias Functions

4.2.1 LBLOCA Fuel TIL Thermal Conductivity Modeling

There are two primary factors contributing to large temperature differences across the gap in RELAP5 at steady state. The first effect is due to the VAFT uncertainty plus the TCD bias factor at MOL and EOL. The second is use of a BOL thermal conductivity for the fuel pellet at these higher burnups. The bias factor is required to account for TCD during TIL applications. Adding a degraded fuel thermal conductivity in RELAP5 is consistent with the effects of TCD and decreases the temperature difference across the gap such that the gap multiplier does not have to compensate for this effect. Therefore, fuel thermal conductivity curves for use in RELAP5 for TIL analyses are developed.

Figure 4-5 adds several radial temperature profiles to the Figure 4-4 curves to help in showing how the fuel thermal conductivity changes the mesh point temperatures at steady state. The first is the COPERNIC2 best-estimate temperature (labeled as "COPERNIC BE"), which includes the TCD effects at a rod average burnup of 34 GWd/mtU. Note that the mesh point temperatures for COPERNIC2 and TACO3 shown in Figure 4-5 are based on hot expanded geometry where the RELAP5 temperatures are based on cold radii. The radial dimension shifts are most obvious at the fuel and clad interface and the outside clad radius.

The curve from Figure 4-4, labeled "RELAP 95/95 w Generic TCD Bias Factor", is shown on Figure 4-5 with a more descriptive label of "RELAP 95/95 w Generic TCD Bias Factor for BOL Fuel Thermal Conductivity". Also added to this Figure 4-5 is a new RELAP5 temperature profile targeting the same VAFT, but with a reduced thermal conductivity applied to the fuel (labeled as "RELAP 95/95 w Generic TCD Bias Factor for MOL Fuel Thermal Conductivity"). This revised thermal conductivity changes the fuel pin temperature profile such that it is similar to the COPERNIC2 shape. [

]

The fuel stored energy removal during the majority of the transient with an open gap is controlled by the gap gas conductivity. This heat removal should not be significantly influenced by a skewed multiplier calculated at steady-state conditions. Since the gas thermal conductivity models are similar between the steady-state fuel pin codes and RELAP5, [ ] during the transient. [ ] The original intent of including the gap gas multiplier was to adjust the fuel-gap conductance in the over-constrained input until the desired VAFT was matched at steady-state.

The product of the gap multiplier and the gap gas conductance shown in Equation 8 is further expanded in Equation 9 (Equation 2.3.2-3 in Reference 2). It is computed based on eight azimuthal gap sections that vary from having the fuel pellet and clad being just in contact on one side and open to twice the nominal gap width, T_{gap}, on the opposite side.

Equation 9

$$M_{gap\,gas} * h_{gap\,gas} = \frac{M_{gap\,gas} * k_{gas}}{8} * \sum_{n=1,8} 1/\left[\tau_{gap\,n} + 3.6\left(R_f + R_c\right) + (g_1 + g_2)\right]$$

$$h_{gap\,gas} = k_{gas}/8 * \sum_{n=1,8} 1/\left[\tau_{gap\,n} + 3.6\left(R_f + R_c\right) + (g_1 + g_2)\right]$$

where:

$h_{gap\,gas}$ = total gap gas conductance

$M_{gap\,gas}$ = gap gas thermal conductivity multiplier

k_{gas} = composite gas thermal conductivity

τ_{gap} = nominal gap width

R_{fuel} = fuel pellet surface roughness

R_c = clad inside surface roughness

$(g_1 + g_2)$ = temperature jump distance

Figure 4-4 MOL LOCA Initialization using BOL Fuel Thermal Conductivities to Determine Fuel Radial Temperature Distributions

Figure 4-5 MOL LOCA Initialization Fuel Pin Radial Temperature Distributions with TCD

Table 5-1 177-FA LL Plant UO_2 Fuel MOL LOCA Cases

Parameter	OEA	S+TCD	S+TCD+RLHR
Core Axial Peaking Elevation, ft	2.506	2.506	2.506
HP Rod Average Burnup, GWd/mtU	34	34	34
HP Peak Power Local Burnup & Elevation, GWd/mtU/Elev., ft	37.8 / 2.5	37.8 / 2.5	37.8 / 2.5
HP Maximum Local Burnup & Elevation, GWd/mtU/ Elev., ft	41.4 / 5.5	41.4 / 5.45	41.4 / 5.45
HP Nuclear Source Linear Heat Rate, kW/ft	17.8	17.8	16.8
HP Initial UO_2 Peak VAFT, F	2321.9	2535.0	2413.6
HP Maximum Best-Estimate UO_2 VAFT, F	2085.5	2004.4	1895.5
Initial HP Rod Internal Pressure, psia	1898.0	1722.8	1621.3
HB Rod Average Burnup, GWd/mtU	34	34	34
HB Nuclear Source Linear Heat Rate, kW/ft	17.8	17.8	16.8
HB Initial UO_2 Peak VAFT, F	2147.1	2454.1	2331.6
Initial HB Rod Internal Pressure, psia	1898.0	1722.8	1621.3
Transient			
Break Opening Time, sec	0	0	0
End of Bypass Time, sec	17.1	17.1	17.2
End of Blowdown Time, sec	22.3	22.3	22.4
Bottom of Core Recovery Time, sec	27.5	27.5	27.5
End of Transient, sec (10 sec after AC quench)	169.3	169.1	168.7
HP Ruptured Segment PCT, F	1750.9	**2212.3**	1890.2
HP Ruptured Segment PCT Time, sec	27.9	30.4	28.0
HP Peak Unruptured Segment PCT, F	**1851.9**	2132.1	**1933.2**
HP Peak Unruptured Segment PCT Time, sec	27.9	28.0	28.0
HP Maximum Local Oxidation, %	1.72	5.18	2.16
HB Ruptured Segment PCT, F	1658.1	2064.6	1808.8
HB Ruptured Segment PCT Time, sec	27.9	28.0	28.0
HB Peak Unruptured Segment PCT, F	1707.7	2056.8	1871.2
HB Peak Unruptured Segment PCT Time, sec	32.9	28.0	32.9
HP Maximum Local Oxidation, %	1.59	3.38	1.86
Whole Core Hydrogen Generation, %	<0.06	<0.15	<0.08

Table 5-2 177-FA LL Plant Gadolinia Fuel MOL LOCA Cases

	2 w% Gadolinia			4 w% Gadolinia			6 w% Gadolinia			8 w% Gadolinia		
Parameter	**OEA**	**S+TCD**	**S+TCD +RLHR**	**OEA**	**S+TCD**	**S+TCD +RLHR**	**OEA**	**S+TCD**	**S+TCD +RLHR**	**OEA**	**S+TCD**	**S+TCD +RLHR**
Rod Average Burnup, GWd/mtU	34	34	34	34	Unanalyzed	34	34	Unanalyzed	34	34	34	34
Core Axial Peaking Elevation, ft	2.506	2.506	2.506	2.506	Unanalyzed	2.506	2.506	Unanalyzed	2.506	2.506	2.506	2.506
Gadolinia Rod to UO_2 LHR Ratio	0.95	0.95	0.95	0 .91	Unanalyzed	0 .91	0 .88	Unanalyzed	0 .88	0 .85	0 .85	0 .85
NS Linear Heat Rate, kW/ft	16.9	16.9	15.9	16.1	Unanalyzed	15.2	15.6	Unanalyzed	14.7	15.1	15.1	14.1
Peak Power Local Burnup, GWd/mtU/Elev., ft	39.0 / 2.5	39.0 / 2.5	39.0 / 2.5	39.2 / 2.5	Unanalyzed	39.2 / 2.5	39.3 / 2.5	Unanalyzed	39.3 / 2.5	39.4 / 2.5	39.4 / 2.5	39.4 / 2.5
Maximum Local Burnup, GWd/mtU/ Elev., ft	39.5 / 3.1	39.5 / 3.1	39.5 / 3.1	39.6 / 3.1	Unanalyzed	39.6 / 3.1	39.7 / 3.1	Unanalyzed	39.7 / 3.1	39.8 / 3.1	39.8 / 3.1	39.8 / 3.1
Initial Pin Peak VAFT, F	2290.9	2565.5	2439.8	2327.8	Unanalyzed	2477.4	2341.7	Unanalyzed	2496.1	2307.7	2604.8	2472.8
Max Best-Estimate Pin Peak VAFT, °F	2057.8	1995.9	1882.8	2090.9	Unanalyzed	1917.4	2103.3	Unanalyzed	1933.3	2072.8	2031.0	1912.4
Initial Rod Internal Pressure, psia	1744.5	1598.9	1482.6	1823.0	Unanalyzed	1565.5	1769.8	Unanalyzed	1523.8	1697.2	1582.4	1469.6
Ruptured Segment PCT, F	1713.9	**2145.9**	1861.6	1732.0	Unanalyzed	1901.2	1733.7	Unanalyzed	1901.9	1704.3	**2131.3**	1858.7
Ruptured Segment PCT Time, sec	27.9	28.0	28.0	27.9	Unanalyzed	28.0	27.9	Unanalyzed	28.0	27.9	28.0	28.0
Peak Unruptured Segment PCT, F	**1783.4**	2095.4	**1905.2**	**1806.1**	Unanalyzed	**1934.3**	**1790.8**	Unanalyzed	**1931.8**	**1736.8**	2071.1	**1896.3**
Peak Unruptured Seg PCT Time, sec	27.9	28.0	28.0	27.9	Unanalyzed	28.0	27.9	Unanalyzed	28.0	27.9	28.0	28.0
Maximum Local Oxidation, %	1.62	4.30	2.04	1.65	Unanalyzed	2.20	1.65	Unanalyzed	2.20	1.56	4.07	2.01

Table 5-3 177-FA LL Plant UO_2 Fuel EOL LOCA Cases

Parameter	OEA[Note 1]	S+TCD
Core Axial Peaking Elevation, ft	2.506	2.506
HP Rod Average Burnup, GWd/mtU	62	62
HP Peak Power Local Burnup & Elevation, GWd/mtU/Elev., ft	69.3 / 2.5	69.3 / 2.5
HP Maximum Local Burnup & Elevation, GWd/mtU/ Elev., ft	73.5 / 4.9	73.5 / 4.9
HP Nuclear Source Linear Heat Rate, kW/ft	12.3	12.3
HP Initial UO_2 Peak VAFT, F	1850.4	2320.1
HP Maximum Best-Estimate UO_2 VAFT, F	1638.3	1558.5
Initial HP Rod Internal Pressure, psia	2970.6	2504.2
HB Rod Average Burnup, GWd/mtU	62	55
HB Nuclear Source Linear Heat Rate, kW/ft	69.3 / 2.5	61.3 / 2.5
HB Initial UO_2 Peak VAFT, F	73.5 / 4.9	65.9 / 4.9
Initial HB Rod Internal Pressure, psia	12.3	13.4
Transient		
Break Opening Time, sec	0	0
End of Bypass Time, sec	20.4	18.317.1
End of Blowdown Time, sec	22.3	22.3
Bottom of Core Recovery Time, sec	29.3	27.5
End of Transient, sec (10 sec after AC quench)	171.1	169.5
HP Ruptured Segment PCT, F	**1618.3**	1710.3
HP Ruptured Segment PCT Time, sec	31.63	27.9
HP Peak Unruptured Segment PCT, F	1577.0	**1769.7**
HP Peak Unruptured Segment PCT Time, sec	31.8	32.6
HP Maximum Local Oxidation, %	1.92	2.35
HB Ruptured Segment PCT, F	1559.7	1682.2
HB Ruptured Segment PCT Time, sec	31.4	27.9
HB Peak Unruptured Segment PCT, F	1522.1	1747.2
HB Peak Unruptured Segment PCT Time, sec	31.7	32.6
HP Maximum Local Oxidation, %	1.86	1.76
Whole Core Hydrogen Generation, %	< 0.03	<0.04

Note 1: The original EOL EM analyses did not have column weldments modeled in the RELAP5 blowdown model. The analysis also contained an error in the end of bypass calculations. An evaluation showed that the PCT change when the CW model is included and the ECCS bypass error corrected is 0 F. Therefore, the PCT report for this case effectively accounts for CW modeling and ECCS bypass correction along with the filtered flow error estimated PCT change of 0 F. The BOCR time and PCT are later by ~2 seconds because of the bypass error.

Table 5-4 177-FA LL Plant Gadolinia Fuel EOL LOCA Cases

	2 w% Gadolinia		4 w% Gadolinia		6 w% Gadolinia		8 w% Gadolinia	
Parameter	**OEA[Note 1]**	**S+TCD**	**OEA[Note 1]**	**S+TCD**	**OEA[Note 1]**	**S+TCD**	**OEA[Note 1]**	**S+TCD**
Rod Average Burnup, GWd/mtU	62	55	62	55	62	55	62	55
Core Axial Peaking Elevation, ft	2.506	2.506	2.506	2.506	2.506	2.506	2.506	2.506
Gadolinia Rod to UO_2 LHR Ratio	0 .95	0.95	0 .91	0.91	0 .88	0.88	0 .85	0.85
NS Linear Heat Rate, kW/ft	11.6	12.7	11.1	12.2	10.8	11.8	10.4	11.4
Peak Power Local Burnup, GWd/mtU/Elev., ft	70.3 / 2.5	62.4 / 2.5	70.5 / 2.5	62.6 / 2.5	70.7 / 2.5	62.8 / 2.5	70.9 / 2.5	63.0 / 2.5
Maximum Local Burnup, GWd/mtU/ Elev., ft	70.7 / 3.1	63.0 / 3.1	70.9 / 3.1	63.2 / 3.1	71.1 / 3.1	63.4 / 3.1	71.4 / 3.1	63.6 / 3.1
Initial Pin Peak VAFT, F	1961.8	2352.5	1984.3	2427.5	2017.9	2437.2	2021.9	2437.6
Max Best-Estimate Pin Peak VAFT, F	1617.6	1622.5	1636.1	1681.8	1663.7	1690.8	1667.0	1691.0
Initial Rod Internal Pressure, psia	2693.9	2044.5	2705.9	2270.4	2797.3	2136.1	2749.0	2083.0
Ruptured Segment PCT, F	**1581.8**	1727.0	**1581.3**	1741.7	**1598.0**	1749.0	**1594.5**	1758.4
Ruptured Segment PCT Time, sec	31.5	27.9	31.5	27.9	31.5	27.9	31.5	27.9
Peak Unruptured Segment PCT, F	1556.4	**1754.3**	1566.7	**1806.0**	1578.7	**1801.7**	1575.8	**1783.9**
Peak Unruptured Seg PCT Time, sec	31.8	32.6	31.8	32.6	31.8	32.6	31.8	32.6
Maximum Local Oxidation, %	2.18	2.12	2.41	2.20	2.42	2.37	2.30	2.29

Note 1: The original EOL EM analyses did not have column weldments modeled in the RELAP5 blowdown model. The analysis also contained an error in the end of bypass calculations. An evaluation showed that the PCT change when the CW model is included and the ECCS bypass error corrected is 0 F. Therefore, the PCT report for this case effectively accounts for CW modeling and ECCS bypass correction along with the filtered flow error estimated PCT change of 0 F. The BOCR time and PCT are later by ~2 seconds because of the bypass error.