TECHNICAL EVALUATION REPORT OF THE
TOPICAL REPORT BAW-10184P, ENTITLED
"GDTACO: URANIA-GADOLINIA FUEL PIN
THERMAL ANALYSIS CODE"

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ABBREVIATIONS

BWFC	Babcock & Wilcox Fuel Company
BNFL	British Nuclear Fuels, Limited
EPRI	Electric Power Research Institute
FGR	Fission Gas Release
FIN	Financial Identification Number
LHGR	Linear Heat Generation Rate
LOCA	Loss-of-Coolant Accident
NRC	U.S. Nuclear Regulatory Commission
PCT	Peak Cladding Temperature
PNL	Pacific Northwest Laboratory
TER	Technical Evaluation Report
TH	Thermal-Hydraulic

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1.0 INTRODUCTION

This Technical Evaluation Report (TER), prepared for the U.S. Nuclear Regulatory Commission (NRC) by Pacific Northwest Laboratory (PNL)[a] under Financial Identification Number (FIN) I2009, is a review of the methodology by which Babcock and Wilcox Fuel Company (BWFC) will evaluate the fuel performance behavior of rods containing urania-gadolinia pellets. This methodology is described in the topical report BAW-10084P (Reference 1), and was amplified by BWFC's letter of May 19, 1993, (Reference 2) in response to the NRC's request for additional information (Reference 3). The models, analytical methods, and procedures used by BWFC to evaluate the performance of sintered urania-gadolinia fuel pellets containing limited additions of gadolinia are described in Reference 1 and are reviewed in this TER. PNL has acted as a consultant to the NRC in this review.

BWFC's proposed addition of gadolinia is nominally limited to 8.0 wt% gadolinia with an upper limit of 8.3 wt.%. In proposing to operate urania-gadolinia fuel rods with gadolinia contents up to this limit, BWFC recognizes that the pellet physical properties are altered relative to those of urania-only pellets and that, in particular, the thermal conductivity of the urania-gadolinia pellet material will be less than that of urania-only pellets at equivalent temperatures. BWFC states that the neutron-absorption properties of the gadolinia, plus the rod placement and operation within the fuel assembly design, will combine in such a way that the urania-gadolinia rods will in most cases not be the power limiting rods in the core; however, this possibility is not excluded.

BWFC's standard fuel rod thermal analysis code for urania fuel rods is the TACO3 code (Reference 4). The GDTACO code is identical to the TACO3 code with the exception of the thermal analysis model changes made to account for urania-gadolinia properties as described in Reference 1. This reference also contains the results of best-estimate and bounding calculations of integral

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fuel rod parameters, in particular the fuel rod internal gas pressure as a function of burnup.

This evaluation is divided into examination of 1) the proposed urania-gadolinia physical properties; and 2) the analytical methods and methodology BWFC will use to evaluate performance of rods containing urania-gadolinia pellets. These evaluations will be found in Sections 2 and 3, respectively.

2.0 URANIA-GADOLINIA PHYSICAL PROPERTIES

The physical properties or calculational attributes of urania fuel pellets that BWFC has altered due to gadolinia addition include the following: 1) fuel pellet thermal conductivity; 2) radial power profiles; and 3) fuel solidus temperature. Although not listed in the original GDTACO document, the pellet density is also altered by gadolinia addition as explained in Section 2.5. A significant increase in fuel specific heat at elevated temperatures (compared to that of urania) was originally proposed, but was subsequently withdrawn (Reference 2).

Urania-gadolinia pellets are produced from high-energy milled UO_2 and Gd_2O_3 mixed powders, which are first cold-pressed at high pressure into pellets and then sintered at high temperature in a reducing atmosphere, under conditions similar to the production of urania fuel pellets. The final product is primarily a solid solution of the chemical form $(U_{1-y}, Gd_y)O_2$, where "y" is the atom fraction of Gd in the Gd,U mix. The particle size and absolute quantity of non-solution urania and gadolinia particles are tightly controlled, and the stoichiometry, density, and purity of the sintered pellets are also tightly controlled. BWFC has provided a description of the manufacturing controls, and asserts that, for calculational purposes, the urania-gadolinia pellets to which GDTACO will be applied are identical to the samples for which thermal properties (in particular thermal diffusivity) have been measured. BWFC further asserts that no further explicit calculational adjustments must be made in GDTACO to account for stoichiometry or homogeneity variations, as long as the code is applied to fuel pellets that meet the control limits. PNL concludes that this assertion is acceptable.

2.1 THERMAL CONDUCTIVITY

Measurements of the thermal diffusivity of urania-gadolinia pellet type material were performed under Electric Power Research Institute (EPRI) sponsorship at PNL and at British Nuclear Fuels, Limited (BNFL). These measurements were reported in Reference 5. The gadolinia contents investigated included 4, 8, and 12 wt%; and the thermal diffusivity measurements extended to 1900 K. The thermal conductivity, "K", is related to the thermal diffusivity, "a", the density, "d", and the specific heat, "C_p", by the equation:

$$a = \frac{K}{(dC_p)}$$

Ideally, the thermal conductivity would be derived from the diffusivity data, using specific heat and density measurements made on the same samples or companion samples. However, companion specific heat measurements only extended to 1400 K. Therefore, BWFC originally chose to use the heat capacity data measured to 1500 K by Inaba (Reference 6) for deriving the thermal conductivity, with rules for extrapolation toward the urania-gadolinia melting temperature (at approximately 3000 K) as suggested by Thornton (Reference 7).

PNL concludes that Dr. Thornton's logic and mathematical formulations for making the derivations and extrapolations of thermal conductivity (Reference 7) are reasonable. However, there is not wide acceptance for the "excess heat capacity" which Inaba et al. (Reference 6) have found at temperatures in the 800 to 1500 K range for urania-rare earth mixtures. Most researchers find only a small (2 to 3%) increase in heat capacity over this temperature range due to the additions of up to 10 wt% rare earths, as opposed to the much higher increases found by Inaba et al. (see, for example, Reference 8). When the Inaba et al. specific heat data are applied to the EPRI thermal diffusivity data, the resulting thermal conductivity as a function of gadolinia content and temperature becomes <u>higher</u> than that of urania at temperatures above 1600 K. This behavior is not consistent with previous observations, where most researchers have found the thermal conductivity of urania-rare earth mixtures to be <u>less</u> than that of urania, up to temperatures as high as 2400 K. (See, for example, References 5, 8, and 9).

Therefore, PNL/NRC suggested (Reference 3) that BWFC re-derive the thermal conductivity functions using the specific heat of urania-only pellets. This was done, and resulted in thermal conductivity functions that were uniformly less than that of urania-only, and only approached the latter at very high temperatures. BWFC agreed to use these re-derived thermal conductivity values in GDTACO, and revised the code and its application calculations accordingly (Reference 2).

However, BWFC pointed out that, when the re-worked thermal conductivity is used to calculate pellet temperatures, the only "physically consistent" choice for specific heat to be used in the calculation of stored energy and rod heat content, for loss-of-coolant accident (LOCA) simulation calculations, is the urania-only specific heat.[a] BWFC currently proposes (Reference 2) to apply a widely accepted expression for urania specific heat as a function of temperature (e.g., Reference 10) in the calculation of urania-gadolinia pellet stored energy. PNL concludes that this proposal is acceptable.

The actual impact of all these changes to the calculated stored energy was very small (less than 2%), due to the offsetting effects of lower thermal conductivity and lower heat capacity. However, GDTACO now contains a set of thermal conductivity functions that are defensible in terms of previously accepted measured data and data trends. Higher values of urania-gadolinia thermal conductivity, as originally proposed by BWFC, should be supported by more direct and complete measurements over the temperature range of interest, and by mechanistic study of the interrelated thermal properties of urania-gadolinia, before being accepted.

2.2 RADIAL POWER PROFILES

The effect of gadolinia addition on the radial power profile within the pellet, and its evolution with increasing burnup, is sufficiently significant that radial power profiles generated for low-enriched urania pellets cannot be used for calculation of fuel temperatures. Power profiles versus fuel pellet burnup have been generated by BWFC using the neutronics code MICBURN specific to each application of gadolinia content and pellet radius, and these are used in GDTACO.

The mechanistic causes of the evolution of radial power profile with burnup are as follows. At beginning-of life (0 to 5000 MWd/MTU), the

[a] BWFC had been using the specific heat functions derived by Thornton from the Inaba heat capacity measurements, for fuel enthalpy calculations.

gadolinium at the pellet edge is "burning out," that is, the high cross-section isotopes capture thermal neutrons and transmute to lower cross-section isotopes. This causes progressively edge-peaked profiles. This process continues but diffuses as the burnout front disperses inward. Finally, from about 20,000 MWd/MTU onward, plutonium build-in on the pellet edge due to resonance neutron captures by ^{238}U leads to a second but more gradual development of peak power at the edge of the pellet. At burnups of 40,000 MWd/MTU and above, the pellet profile resembles that of a urania-only rod of comparable burnup.

BWFC asserts that the pellet radial power profiles developed by MICBURN and used in GDTACO represent reasonable evolutions of the power distribution with burnup; the MICBURN code has been found acceptable by NRC (Reference 11). PNL concludes that radial power profiles developed in this manner are acceptable.

2.3 PELLET SOLIDUS TEMPERATURE

Based on melt temperature measurements reported in Reference 5, BWFC has proposed that the pellet solidus temperature not be reduced due to gadolinia addition for gadolinia contents less than or equal to 8 wt%. PNL has reviewed the data and concludes that this recommendation is acceptable. PNL notes, however, that other researchers have found slight reductions in the melting temperature due to limited rare earth additions (References 12 and 13). The melting temperature is, however, reduced in GDTACO as a function of increasing burnup; and it is effectively reduced to account for code uncertainties and manufacturing uncertainties. BWFC asserts that this large reduction covers the uncertainty attendant to both gadolinia effects and uncertainties in code-calculated temperatures. PNL concludes that this assertion is acceptable.

2.4 FUEL PELLET SWELLING AND DENSIFICATION

As a consequence of gadolinia addition, BWFC has made a very slight change to the fuel swelling rate contained in the TACO3 code. BWFC has compared code predictions of pellet density to measured densities urania-gadolinia pellets with burnups in the range from 2,000 to 50,000 MWd/MTU and gadolinia contents of 4 and 8 wt%. On the basis of these comparisons, presented in Reference 1, PNL concludes that the combined swelling and densification model in GDTACO is acceptable for the proposed application to urania-gadolinia fuel.

2.5 PELLET DENSITY

The density of the sintered urania fuel pellets is reduced by the addition of gadolinia. The extent of the reduction is not large; however, it was not given in the original GDTACO document. PNL/NRC requested the relationship and obtained it in the supplementary transmittal from BWFC (Reference 2).

This relationship was checked by PNL against measured densities for the sintered urania-gadolinia diffusivity samples listed in Reference 5. PNL concludes that the relationship is acceptable.

2.6 OTHER (UNALTERED) MODELS IN GDTACO

Other models for fuel properties and thermal performance calculations in TACO3 remain unchanged in GDTACO. In particular, PNL notes the following.

2.6.1 Porosity Correction Factor

The correction for fuel pellet porosity which BWFC applies to the 100% theoretical density thermal conductivity values remains unchanged, based on the observation that the porosity size distributions and morphologies in urania and urania-gadolinia pellets of comparable porosity fractions are very similar. PNL concludes that this is acceptable.

2.6.2 Fuel Pellet Thermal Expansion and Relocation

Based on measurements reported in Reference 5 and elsewhere, BWFC concludes that the thermal expansion of urania-gadolinia pellets with gadolinia content up to the nominal 8 wt% is indistinguishable from that of pure urania pellets. BWFC also retains the same mechanical outward relocation function in the code for relocation caused by fuel cracking and pellet fragment outward ratcheting, based on the observation that thermal stresses and cracking patterns for the two types of pellets are similar. PNL has reviewed the references, and concludes that this is acceptable.

2.6.3 Fission Gas Release

BWFC points out that the body of data on fission gas release (FGR) for urania-gadolinia rods with gadolinia contents and power histories of interest for this application, is extremely limited. BWFC does present limited comparisons in Reference 1 that indicate that the TACO3 FGR model results in best-estimate or conservative predictions of the limited FGR data available that are applicable. On the basis of these comparisons, BWFC recommends retaining the TACO3 FGR models and equation in their unaltered form in GDTACO. PNL concludes that this is acceptable, but notes that the issue of FGR must be revisited if application is made to gadolinia contents greater than the nominal 8 wt%.

3.0 ANALYTICAL METHODS AND FUEL PERFORMANCE CODE APPLICATION

BWFC lists the following fuel rod performance analyses, for which the GDTACO code will be applied to urania-gadolinia rods:

1. Margin to fuel melting
2. Fuel rod internal gas pressure
3. Cladding strain
4. Creep Collapse calculation initiation
5. Loss-of-coolant-accident calculation initiation.

These analyses will be discussed in turn below. In some cases, BWFC has presented sample calculations. In most cases, PNL has also performed audit calculations, utilizing the audit code GAPCON-THERMAL-2, Revision 2 (GT2R2) (Reference 14) with the modified ANS5.4 FGR model and best-estimate fuel relocation.

3.1 POWER MARGIN TO FUEL MELTING

As described in Section 2.3, BWFC assesses the margin between peak operating linear heat generation rates (LHGR's) and that required to produce centerline fuel melting, by comparing calculated centerline temperatures at various LHGRs to a "limit temperature." This comparison is done at preselected burnups and axial nodes, using the SLICE option in the code, as described and approved for the TACO3 code (Reference 4). The limiting melt temperature is found by reducing the urania solidus temperature by a proprietary amount to account for code uncertainties, and by making a further burnup-dependent reduction to account for burnup effects. No reduction is made explicitly for gadolinia additions up to 8 wt%, based on data presented in Reference 5.

Based on conversations with BWFC and their response (Reference 2) to the request for additional information (Reference 3), BWFC has agreed to assess the margins between peak rod powers and the power-to-melt separately for both the urania and the urania-gadolinia rods, by using the TACO3 code for the urania rods and the GDTACO code for the urania-gadolinia rods. The margins for the urania-gadolinia rods are expected to be uniformly less than those for the urania-only rods because the neutronic effect of the gadolinia in lowering power level and altering the radial power profile will more than compensate for the degradation of pellet thermal conductivity in equivalent neutron fluxes. BWFC has agreed to verify that the urania-only rods are the limiting type, on a cycle-specific basis. If the urania-gadolinia rods do prove more limiting, core/assembly power levels will be adjusted to assure that the margins are not degraded due to the introduction of urania-gadolinia rods in the fuel assembly design.

Sample power-to-melt audit calculations PNL has performed at mid-life for both urania and urania-8 wt.% gadolinia Mark B rods indicate that the reduction in power-to-melt due to gadolinia addition is compensated by the reduced peak powers which BWFC predicts for the gadolinia rods. The result is that the power margin to melt is greater for the gadolinia rods.

Based on the foregoing discussion, PNL concludes that the proposed methodology for determining power-to-melt and margin-to-melt is acceptable.

3.2 FUEL ROD INTERNAL GAS PRESSURE

The method by which BWFC proposes to make "best-estimate" calculations of fuel rod internal gas pressure versus burnup for urania gadolinia rods is similar to the methodology reviewed and approved previously for the same analysis for urania-only rods, using the TACO3 code. It should be noted that the BWFC "best-estimate" methodology for applying GDTACO does, in fact, contain some conservatism with respect to the model formulations within GDTACO and with respect to the selected power history. A power history is selected for the rod, which is detailed with respect to: rod-average power changes; axial power profile, and changes to axial power profile; and changes to pellet radial power profiles. This power history also includes power transients at 10,000 MWd/MTU increments, which conservatively simulate unlikely but possible power transients for a given rod due to control rod position changes. The GDTACO code is run with this power history, and the evolving fuel rod pressure is accumulated and plotted.

BWFC presents sample calculations for the Mark B and Mark BW fuel rod designs, with 4 wt% and 8 wt% gadolinia contents. These examples indicate that, on a best-estimate basis, these rods will not exceed the pressure limits histories indicate that system pressure would be exceeded just before end-of-life, but this result has been traced to very large FGR fractions predicted by the ANS5.4 gas release model during the end-of-life power/temperature transients at high burnup.

BWFC's method for estimating the "bounding" pressure history for a peak rod parallels exactly the methodology reviewed and approved previously for urania-only rods using the TACO3 code (Reference 4). Penalties (in units of pressure) are added to the best-estimated pressure calculation, to account for manufacturing uncertainties, code calculational uncertainties, and power history uncertainties.

The manufacturing uncertainties are bounded, and their separate pressure effects are calculated individually. These are then statistically combined to produce an overall penalty due to manufacturing uncertainty. The power history penalty is assessed by adding a proprietary fraction to the envelope power history, as was done for TACO3. The code uncertainty penalty is assessed at specific burnups by running a Monte Carlo routine for pressure calculations several thousand times at each of those burnups. The input for the Monte Carlo routine is rod void volumes and their associated temperatures and uncertainties, which come directly from the GDTACO output.

The code, manufacturing, and power history uncertainties are viewed as independent, so the associated pressure penalties are statistically combined to obtain a total pressure penalty at each burnup evaluated. These overall pressure penalties are then added to the best-estimate pressure history, to obtain "bounding" pressure histories. The pressure histories in the examples in Reference 1 provide bounding internal pressures for the urania gadolinia rods.

In assessing the pressure histories, BWFC reserves the option to compare either to system pressure or to the limit set forth in Reference 15. However, actual use of the criterion in Reference 15 must await approval of that document by NRC.

PNL's audit code calculations indicate that BWFC's methodology for producing "bounding pressure histories" is sufficiently conservative to provide an upper bound to actual fuel rod pressure performance. By the provide an upper bound to actual fuel rod pressure performance. By the modifications inherent in the GDTACO code, BWFC has accounted for all the additional aspects related to gadolinia addition which impact the calculation of fuel rod internal pressure. Applying the TACO3 pressure history bounding methodology with the GDTACO code is a conservative, and therefore acceptable, analysis procedure for urania-gadolinia rods with up to the nominal 8 wt% gadolinia content.

Based on the foregoing discussion, PNL concludes that BWFC's proposed methodology for calculating fuel rod internal gas pressure is acceptable for application to urania-gadolinia rods up to the nominal 8 wt% gadolinia content.

3.3 CLADDING STRAIN CALCULATIONS

The GDTACO code will be used to assess the cladding permanent strain against the 1% limit for cladding (permanent) strain, achieved in power transients. The methodology for this analysis is similar to that applied to urania-only rods using TACO3, and involves altering the GDTACO code input to promote fuel-cladding mechanical interaction and cladding straining rates. These input alterations include using the bounding power histories, nominal fuel/cladding dimensions, and imposed (conservative) estimates of oxide layer thickness along the length of the rod. PNL concludes that this analysis methodology is acceptably conservative.

3.4 CREEP COLLAPSE CALCULATION INITIATION

The philosophy by which GDTACO will be used to generate input information for creep collapse analyses is similar to that applied to cladding strain calculations: conservative choices of code input are made to produce conservatively biased output. The parameters influencing creep collapse include rod internal gas pressure and cladding operating temperatures. To minimize the internal pressure, the fission gas release model is turned off. To maximize cladding temperatures, bounding power histories are input and conservative estimates of oxide layer thicknesses and its thermal conductivity are applied. PNL concludes that this analysis methodology is acceptably conservative.

3.5 LOCA SIMULATION CALCULATION INITIATION

The GDTACO code will be used to establish initial conditions for thermal-hydraulics (TH) codes used to perform loss-of-coolant accident analyses. The only parameters actually passed between the codes include cold-state dimensions and steady-state operating temperatures. The code uncertainty factor (i.e., 95/95 tolerance bound) found in comparison of TACO3 calculated centerline temperatures to in-reactor measured data is conservatively applied to the GDTACO output volume-average temperatures. The TH codes are forced to initiate themselves with these augmented volume-average temperatures. Fuel stored energy is calculated in these codes for the urania-gadolinia rods by using the specific heat function versus temperature for pure urania, as discussed earlier (Section 2.1).

The initial-condition temperatures for LOCA are derived by running the rod design with the envelope power history to a burnup range judged to maximize peak cladding temperature (PCT) in LOCA. For a urania-gadolinia rod, this would be in the 10,000 to 40,000 MWd/MTU range, essentially where the gadolinia effect has burned out but the ^{235}U depletion is not complete. In this burnup range, the rod is ramped up to a LOCA-initiation power level, determined by ratio to the corresponding level for a urania-only rod.

Comparative LOCA calculations were performed by BWFC, at PNL's request, with the original and re-worked pellet thermal conductivity values, for the Mark B rod with 8 wt% gadolinia content. The results were extremely close, with GDTACO inputs known to result in extremely close values of initial fuel stored energy. The comparison between LOCA results and GDTACO output for these two separate cases was a test of the consistency of the methodology, and the close correlation that was achieved supports the adequacy of that methodology.

PNL also performed comparative stored energy calculations (using BWFC's procedures) for a Mark B urania-only rod and a urania-8 wt.% gadolinia Mark B rod, each at their respective envelope power histories. It was found that the gadolinia rod actually had the higher peak-node stored energy during steady-state operation, however the urania rods were more limiting during the imposed power transients. These results emphasize the need for explicit comparisons of stored energy throughout the life of both types of rods, in licensing applications involving both types. A simple comparison of peak-node LHGR's or volume average temperatures alone is not sufficient to identify a burnup range for which the urania-gadolinia rods may become the LOCA-limiting rods.

Based on the foregoing discussion, PNL concludes that BWFC's methodology for TH code LOCA initialization is acceptable for application to urania-gadolinia rods, up to the nominal 8 wt.% gadolinia content.

4.0 CONCLUSIONS

The BWFC GDTACO code is an altered version of BWFC's TACO3 fuel performance code. The modifications include adjusted fuel pellet properties and input parameters that account for the gadolinia addition to the urania up to a nominal 8 wt% (8.3 wt.% maximum). These modifications have been reviewed, together with their effect on integral fuel rod performance parameters, including FGR, fuel rod internal pressure, power-to-melt, and fuel operating temperatures and stored energy. PNL concludes that the modifications are adequately conservative and that their effects on calculated fuel rod performance are acceptable.

The analysis methodology by which BWFC proposes to apply the code in licensing analyses has also been reviewed. PNL concludes BWFCs application methodology is appropriately conservative in all proposed areas of application. Within gadolinia additions up to a nominal 8 wt% (8.3 wt% maximum) PNL concludes that the GDTACO code is acceptable for licensing application to cycle reload analyses for BWFC's Mark B and Mark BW fuel types. This acceptance is contingent, however, on BWFC's agreement to analyze both the urania-only and the urania-gadolinia rods on a cycle-specific basis during each licensing application involving both fuel types. These cycle-specific analyses do not need to be reviewed by NRC as long as they use NRC-accepted analysis methods. Should BWFC wish to not analyze both urania-only and urania-gadolinia rods for cycle-specific applications, justification must be submitted to NRC for review.

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