June 14, 2002

Mr. James Mallay
Director, Regulatory Affairs
Framatome ANP, Richland, Inc.
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: FRAMATOME ANP TOPICAL REPORT BAW-10231, "COPERNIC FUEL ROD DESIGN COMPUTER CODE" - CORRECTION OF ERROR IN SAFETY EVALUATION (TAC NO. MA6792)

Dear Mr. Mallay:

By letter dated April 18, 2002, the NRC staff transmitted its safety evaluation (SE) on BAW-10231 to Framatome ANP. In a May 1, 2002, letter, you notified us that the SE contained an error on page 6. Therefore, the second sentence of Section 5.0, "Fuel Densification and Swelling Models" is modified to read: "The modeling of fuel densification and solid swelling in COPERNIC are included together as one model for the Integrated Dry Route (IDR) and Ammonium Di-Uranate (ADU) fuel employed by FCF in the U. S. FCF also has a separate densification and swelling model for the Ammonium Uranyl Carbonate (AUC) fuel but this fuel is not used commercially and there are no plans for its use in U. S. plants." The April 18, 2002, SE also contained administrative errors. Therefore, we are reissuing the SE with this letter in its entirety. In accordance with the guidance provided in NUREG-0390, we request that Framatome include this revised SE in the published proprietary and nonproprietary version of this topical report.

We apologize for any inconvenience this may have caused. If you have any questions, please call Drew Holland at (301) 415-1436.

Sincerely,

/RA/

Stephen Dembek, Chief, Section 2
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 693

Enclosure: Corrected Safety Evaluation

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10231P

"COPERNIC FUEL ROD DESIGN COMPUTER CODE"

FRAMATOME COGEMA FUELS

PROJECT NO. 693

1.0 INTRODUCTION

On September 16, 1999, Framatome Cogema Fuels (FCF) submitted to the NRC the revised Topical Report (TR) BAW-10231P (Reference 1), entitled "COPERNIC Fuel Rod Design Computer Code," for review and approval. The COPERNIC computer code is an improved fuel performance code for fuel rod design and analysis of natural, slightly enriched (up to 5 percent) uranium dioxide fuels and urania-gadolinia fuels with the advanced cladding material, M5. Chapter 13 of the TR deals with fuel rod design and analysis of mixed oxide fuel, and will be reviewed later with a separate safety evaluation (SE). FCF uses another approved fuel performance code (TACO3) for licensing applications of zircaloy-4 cladding.

Pacific Northwest National Laboratory (PNNL) acted as a consultant to the NRC for this review. As a result of the NRC staff and PNNL review of the topical report, a request for additional information (RAI) was sent by the NRC to FCF (Reference 2). FCF provided a response to this RAI in Reference 3. Since the issuance of the TR and Reference 3 response, FCF has changed their name to Framatome ANP. The FCF name will be used in this SE.

The SE addresses several major areas of the COPERNIC code including thermal models, material properties, fission gas release, corrosion and hydriding, fuel swelling and densification, mechanical models, and licensing applications. The licensing applications include stored energy and rod pressure inputs to the loss-of-coolant accident (LOCA), maximum rod internal pressures and rod pressure limits, cladding strain, and fuel melting analyses. Audit calculations have been made with the NRC developed FRAPCON-3 fuel performance code for comparison to COPERNIC calculations for maximum rod internal pressure, LOCA temperatures (stored energy) and pressures, temperatures for the fuel melting, and clad strain analyses.

2.0 THERMAL MODELS

2.1 Fuel Thermal Conductivity

The COPERNIC fuel thermal conductivity model is composed of a phonon term and a high-temperature electronic term, and a temperature-dependent porosity correction factor. The phonon term has both a burnup degradation function and a radiation degradation term in its denominator. However, the burnup degradation term is not as dominant as that contained in the Nuclear Fuel Industries (NFI) model, nor as dominant as that in two other recently published thermal conductivity models by Halden (Reference 4) and the French utility Electricite de France (EDF) (Reference 5). Furthermore, the model underpredicts the high temperature conductivity data for unirradiated UO_2 recently published by Ronchi, et al. (Reference 6).

The NRC audit code, FRAPCON-3, currently utilizes two fuel thermal conductivity models: (1) a model proposed by Lucuta, et al. (Reference 7) that was originally used in the code, and (2) an alternate conductivity model proposed by NFI of Japan (Reference 8). The NFI model is based on more recent high burnup thermal conductivity data and provides the best comparisons to both in-reactor fuel temperature and ex-reactor diffusivity data at high burnup (References 9 and 10). The NFI model has a larger degradation in thermal conductivity with fuel burnup than the Lucuta, et al. model, and thus provides higher predicted fuel temperatures with increasing burnup. The staff considers that the NFI model is better than the Lucuta, et al. model for use at high burnups with the FRAPCON-3 code, and it is therefore the primary model used for comparison to the COPERNIC code.

The staff requested (Reference 2) and received FCF information (Reference 3) that provided sufficient detailed design and operating history information to allow for one high-burnup database case comparison calculation (the "EXTRAFORT" rod) with FRAPCON-3. This case involved a re-fabricated high-burnup (58 GWd/MTU) pressurized water reactor (PWR) rod section that was instrumented with a fuel centerline thermocouple and then operated in the OSIRIS test reactor. FRAPCON-3 has been verified against a large amount of high burnup fuel rod data, including fuel centerline temperature measurements. The EXTRAFORT data were also compared with FRAPCON-3 code predictions as further verification of the code. The measured fuel temperatures were slightly under predicted by the FRAPCON-3 code (Lucata thermal conductivity) and slightly overpredicted when the NFI thermal conductivity model was used in the code. The COPERNIC code also slightly overpredicted the temperatures in the EXTRAFORT rod.

The staff (Reference 2) also requested and obtained (Reference 3) a comparison between COPERNIC predictions and data from Halden re-fabricated, instrumented boiling water reactor (BWR) high-burnup rod segment IFA-597.2/3. This rod was base-irradiated to 60 GWd/MTU in the Ringhals BWR and then re-fabricated with a fuel centerline thermocouple and irradiated at a nominal power (20 to 25 kW/m) in the Halden test reactor for approximately 100 days, thereby extending the rod-average burnup to 70 GWd/MTU. The COPERNIC code underpredicted the measured fuel temperatures for this rod near the end of the irradiation at 70 GWd/MTU. FCF also provided COPERNIC predictions of the widely used IFA 562 Rod 16 and 18 (Halden Ultra-High Burnup) data commonly referred to as the HUHB data. These comparisons to the two IFA 562 rods shows that the code underpredicted the temperatures for both rods when rod-average burnups exceed 35 GWd/MTU.

The overall code-data fuel temperature comparisons for COPERNIC indicate that the code predictions compare well to data, or are conservative at low fuel burnups. However, at medium to high burnup, the code’s comparisons to data show mixed results, with a mean prediction of FCF data and an underprediction of the NRC database from the Halden reactor at high burnup. The comparison of the COPERNIC thermal conductivity model to other recently published models, plus in-reactor Halden data, and ex-reactor unirradiated data suggests that the code slightly overpredicts thermal conductivity at moderate to high burnups, and also slightly overpredicts thermal conductivity at low burnups when fuel temperatures approach fuel melting. The small overprediction in fuel thermal conductivity results in a slight underprediction in fuel temperatures for some licensing analyses. Based on an acceptable uncertainty level and good agreement of the temperature predictions between the COPERNIC and NRC audit codes, the staff considers that the thermal conductivity model is acceptable in the COPERNIC code.

2.2 Other Models and Properties

The clad-coolant heat transfer coefficient is calculated as a function of mass flow rate, hydraulic diameter and coolant temperature by the "SAURY" relationship. This was compared to the Dittus-Boelter relationship in FRAPCON-3 and found to be conservative. Because the Dittus-Boelter equation is a standard relationship for the clad and coolant heat transfer, this model is considered acceptable.

The oxide growth model generates a significant oxide layer on the cladding at mid-to-high burnup, even for M5 cladding. The conductivity of this layer as a function of temperature is about 10 to 20 percent higher than the FRAPCON-3/MATRO-11 model. The basis for this conductivity was not given in the original documentation, but in response to RAI question number 22, the basis was stated to be experimental data. The difference between the COPERNIC oxide conductivity and that in FRAPCON-3 is within the uncertainty of this data. Thus, the staff considers that this model is acceptable.

The gap conductance coefficient is the sum of the radiation, gas conduction, and solid-solid contact conduction components. The radiation component is a standard formulation that compares well to FRAPCON-3. The solid-solid contact component is very similar to FRAPCON-3, and compares well to Garnier-Begej (References 11 and 12) ex-reactor data sets for mated Zircaloy-UO2 compacts of varying characterized surface morphologies (roughness) With the good agreement between COPERNIC and FRAPCON-3 codes, the staff considers that the contact conductance model is acceptable for modeling gap conductance for M5 cladding.

The gas conduction function for large fuel-clad gaps is a standard formulation that compares closely to GAPCON/FRAPCON. The gas conduction for small gaps (relative to the fuel/cladding roughness) is the model put forward in 1986 by Wesley and Yavanovich (Reference 13). This model was approved for use in the TACO3 code that has been demonstrated to predict conservatively against the full Garnier-Begej database, including the high-gas pressure database. Because of the approved model, the staff concludes that the gas conduction model is acceptable for the COPERNIC code.

The radial power profile used in COPERNIC is determined from values calculated with the APOLLO2 neutronic transport code (Reference 14) for UO_2 and MOX at different burnup levels. These values are tabulated in COPERNIC and are activated by specifying the U-235 and Pu enrichments. The UO_2-Gd_2O_3 radial powers are entered from a neutronic code calculation of the specific enrichment and core configuration. Examination of the COPERNIC code shows that the radial power profiles become peaked in light-water reactor (LWR) pellets as low as 14 GWd/MTU burnup, according to the APOLLO2 code predictions. The differences between the COPERNIC predicted radial power profiles and those predicted by the TUBRNP model in

FRAPCON-3 are relatively small considering that they have only a small impact on calculated temperatures. Because of the small differences between the COPERNIC and FRAPCON-3 codes, the staff concludes that the radial power profiles are acceptable for the COPERNIC code.

3.0 FISSION GAS RELEASE (FGR) MODEL

Two FGR models operate within the COPERNIC code: a steady-state model and a transient model that tracks the fuel response to rapid power changes.

The COPERNIC steady-state model has two parts: an athermal knockout-recoil component and thermally-activated diffusion component, leading to grain boundary accumulation, saturation, and release.

The athermal portion depends on burnup and rim width and compares slightly conservatively relative to the FRAPCON-3/ANS5.4 athermal model. The athermal model predicts FGR values of less than one percent so that this model is not significant for most analyses that evaluate the limiting rods in a core.

The thermally activated diffusion to the grain boundary results in saturation of the boundary and subsequent release as burnup increases. Once saturation is achieved, the code conservatively assumes that there is an ongoing pathway for release; i.e., once a fuel segment (ring) has achieved saturation, all subsequently produced gas is released from that segment. The diffusion constant is made up of three parts, one of which depends on temperature alone, one on temperature and fission rate, and one on fission rate alone. A comparison of the FRAPCON-3 diffusion coefficients shows that the two match closely at mid-life burnup. The discrepancy at higher burnups is not significant because the power and temperature levels in commercial rods decrease at high burnups and significant FGR is usually encountered as a result of power transients, for which COPERNIC has a completely different model.

The NRC audit code FRAPCON-3 utilizes an athermal release model from ANS 5.4 (Reference 15) and a thermally activated diffusion model proposed by Forsberg and Massih (Reference 16) with modifications to the diffusion coefficient. The COPERNIC predicted cumulative FGR as a function of burnup at constant linear heat generation rate (LHGR) and temperature is similar to that predicted by the Massih model in FRAPCON-3. At high temperatures above 1100°C, the FRAPCON-3 model predicts greater FGR than COPERNIC. FRAPCON-3 predicts a greater FGR than COPERNIC in the range between 900 and 1100°C for burnups greater than 40 GWd/MTU. From 900°C downward, the COPERNIC model predicts more rapid incubation and hence higher FGR in the 40 to 60 GWd/MTU range. However, the overall trend of the COPERNIC FGR model predictions are consistent with the FRAPCON-3 results.

The transient gas release model consists of an enhanced diffusion model for short times, and a burst model that involves controlled release of the grain boundary gas inventory on a time basis related to the current diffusion constant.

The COPERNIC code has been compared against a database of punctured and analyzed fuel rods from LWRs and test reactors that demonstrates that the code provides a best estimate prediction of this data. This database includes a number of test reactor rod cases from steady-state and transient power operation that are typically used for fuel rod performance code validation. However, the data base is sparse for high-burnup fuel rods of U.S. design. Therefore, the staff requested and obtained a code-data comparison for power ramped Mark B rods reported in 1994 (Reference 17). The results showed that the comparison was favorable for the COPERNIC code. In addition, the staff noted in an RAI (Reference 2) that the COPERNIC model did not appear to bound FGR data for urania-gadolinia rods. FCF's response (Reference 3) was to add a multiplier to the temperatures calculated for these rods, which resulted in bounding FGR calculations. The staff considers that this modification is acceptable for the COPERNIC code.

Based on the consistent results between the COPERNIC and FRAPCON-3 codes, the staff concludes that the FGR model in the COPERNIC code is acceptable.

4.0 CLADDING CORROSION AND HYDRIDING MODELS

The waterside corrosion models in COPERNIC are used to predict corrosion during normal operation, are used as input to LOCA analyses, and account for clad thinning in mechanical analyses. The waterside cladding corrosion model for M5 cladding is formulated in a standard way, with pre-transition and post-transition corrosion relationships. The M5 model consists of a pre-transition parabolic rate relationship with an Arrhenius temperature dependence, and a simple post-transition rate relationship, with an Arrhenius temperature dependence. The M5 model coefficients for pre- and post-transition are different from those previously approved in Reference 18 because additional corrosion data have been applied. The transition oxide layer thickness for M5 is near the commonly used value of 2.0 microns for zircaloy.

The FRAPCON-3 code does not have a corrosion model for M5 cladding because this is a new proprietary cladding material used exclusively for FCF fuel designs. However, FRAPCON-3 does have a corrosion model (developed for the Electric Power Research Institute) for zircaloy-4 that has been compared to the COPERNIC model for zircaloy-4 corrosion. The FCF prediction of the corrosion rate for M5 is about ½ to ⅓ of the value predicted by the FRAPCON-3 zircaloy-4 corrosion model. The COPERNIC predicted values for M5 cladding are also about ½ to ⅓ of those observed for FCF zircaloy-4 cladding. The reduced corrosion rate predicted by the COPERNIC M5 corrosion model has been demonstrated to be consistent with in-reactor data for M5 cladding, up to a rod-average burnup of 62 GWd/MTU, i.e., the maximum observed corrosion is about ½ to ⅓ of that for low-tin zircaloy-4 in similar conditions.

Examination of the M5 data from 28 fuel rods from 10 plants (approximately 78 measurements from operation of 1 to 6 cycles) shows that only one data point exists at a rod-average burnup of 62 GWd/MTU and this is from a low duty operational plant. Past experience has shown that fuel rod corrosion is greatest in high duty plants, particularly at high burnup. FCF has provided M5 corrosion data from four high duty plants from Europe with a maximum rod-average burnup of 40 GWd/MTU and have committed to obtain further oxide data at high burnups (Reference 18). It is expected that the corrosion level for M5 cladding will be significantly less than the 100 micron oxide thickness limit for corrosion at rod-average burnups of 62 GWd/MTU even for the high duty plants based on the current M5 data. Based on FCF's commitment to continuously collect corrosion data and use the conservative model, the staff concludes that the M5 corrosion model is acceptable for the COPERNIC code.

The hydrogen pickup fraction recommended for the M5 cladding in COPERNIC is less than the pickup fraction used in FRAPCON-3 for zircaloy-4. The FRAPCON-3 pickup fraction for zircaloy-4 in PWRs is based on a relatively large database of high-exposure U.S. PWR fuel rod cladding. The COPERNIC hydrogen pickup model is consistent with the FCF M5 data base. Based on the conservative way that it models the M5 data, the staff concludes that the M5 hydrogen pickup model is acceptable for the COPERNIC code.

5.0 FUEL DENSIFICATION AND SWELLING MODELS

The fuel densification and swelling models in COPERNIC are important for thermal (LOCA and fuel melting) and cladding strain analyses. The modeling of fuel densification and solid swelling in COPERNIC are included together as one model for the Integrated Dry Route (IDR) and Ammonium Di-Uranate (ADU) fuel employed by FCF in the U.S. FCF also has a separate densification and swelling model for the Ammonium Uranyl Carbonate (AUC) fuel but this fuel is not used commercially and there are no plans for its use in U.S. plants. The maximum fuel densification is determined by FCF in accordance with the recommendation in Regulatory Guide 1.126 (Reference 19). A comparison of the predicted results from COPERNIC (IDR/AUC) and FRAPCON-3 for densification and swelling versus burnup shows that the densification kinetics of the two models are very similar but the COPERNIC solid swelling rate is 15 percent (relative) lower than that predicted by FRAPCON-3. The COPERNIC solid swelling rate is also slightly lower than the rate indicated by the high burnup swelling data used for verification of FRAPCON-3. This will result in a higher burnup level at which hard contact between the fuel and cladding is achieved which is conservative for fuel temperature analyses, but is non-conservative for the cladding strain analysis. This may partially explain why COPERNIC predicts lower clad strain than FRAPCON-3, particularly, at moderate burnups where the fuel-clad gap is closing.

The gaseous swelling model is only used by COPERNIC for thermal analyses and not for the cladding strain analysis. The code comparisons to the thermal data included the use of the gaseous swelling model so that use of the swelling model for thermal predictions is justified. The gaseous swelling model was also used in the prediction of most of their cladding strain data which suggests that it should also be used in their analysis of the 1 percent strain limit. FCF indicated that the strain data used for COPERNIC validation with gaseous swelling came from rods that were ramped to power and held for 1 to 12 hours while the typical transient for the 1 percent strain is a ramp to power that results in immediate scram, i.e., maximum power is for 1 to 2 minutes or less. FCF stated that the elimination of gaseous swelling was justified for this transient because of the short duration of the transient. The expected time frame for these transients will be less than the kinetics of gaseous swelling, and gaseous swelling will be negligible. The staff agrees with this explanation.

Based on the use of conservative models that are consistent with the RG, the staff concludes that the fuel densification and swelling models are acceptable for the COPERNIC code.

6.0 MECHANICAL MODELS

6.1 Modeling

The modeling of mechanical fuel rod behavior by COPERNIC assumes that the pellet is solid (no fuel creep) and the fuel strain determines the amount of elastic-plastic strain in the cladding when hard contact between the fuel and cladding is achieved. Hard contact is initiated when the voids created by the fuel relocation due to the outward movement of fuel fragments are completely consumed by the negative strain due to fuel swelling and thermal expansion. The total fuel strains are calculated from solid swelling, gaseous swelling, densification, thermal expansion, relocation and negative strain models. It is noted that the gaseous swelling model will not be used by COPERINC to predict cladding strains because the use of this model significantly overpredicts some measured cladding strains from fuel rods that were ramped in power. The COPERNIC total cladding strains are calculated from the thermal, creep (slow strain rate), elastic, and high stress creep (fast strain rate) models.

The mechanical model is simplistic in that it assumes a plane strain hypothesis, i.e., cladding deformation in radial and azimuthal directions are independent of the axial stress and strain. The code also assumes isotropic properties of the cladding. Both of these assumptions are not completely accurate for unirradiated stress relief annealed zircaloy-4 fuel cladding, but they are reasonable considering the adequate conservatism in fuel rod mechanical analyses. The cladding loses some of its anisotropic properties as it is irradiated so that it comes closer to isotropic behavior at high burnup.

FCF was questioned by the staff about the mechanical properties for both their zircaloy-4 and M5 cladding types (Reference 2). FCF responded (Reference 3) that at the present time they do not anticipate the use of COPERNIC for licensing their fuel designs with zircaloy-4 cladding in the U.S. The response noted that M5 was expected to be the only cladding used for licensing applications in the COPERNIC code. The M5 mechanical properties of yield strength, ultimate tensile strength, Young's modulus, Poison's ratio, and irradiation growth used in COPERNIC are the same as those approved in the M5 topical report (Reference 18) and, therefore, are acceptable for applications in COPERNIC.

6.2 Irradiation Creep

The M5 creep model in COPERNIC has been modified from that provided in the M5 topical report (Reference 18); however, the differences in predicted creepdown are not significantly different between the two models, particularly within the first 500 days of irradiation when fuel-clad gap closure takes place. The COPERNIC creep model has added a thermal creep component and an irradiation creep component, and the latter component is the most dominant for in-reactor creep (> 95 percent creep is irradiation creep).

The in-reactor creepdown data used to verify the COPERNIC creep model is the same as used in the Reference 14 submittal with the exception that data from two additional rods recently examined at poolside are added to the database. However, the creep database is still very small, with data from only 6 fuel rods with 1 and 2 cycles of operation and 2 rods with 3 cycles of operation. There are several measurements from each fuel rod, but no description of the rod to rod variability that is observed in creep data due to fabrication variability. FCF also presented data from 2 additional rods with 3 cycles of operation that provided a small amount of creepdown data at the rod ends where fuel clad contact had not occurred due to low burnup and swelling. The majority of the axial length of the 3 cycle rods had fuel cladding contact and cannot be used as a measurement of cladding creepdown. A comparison of the M5 creep model from COPERNIC to the in-reactor creepdown data shows a relatively good fit.

FCF proposes to use the uncertainty from their zircaloy-4 creep model for the M5 creep model uncertainties. This uncertainty appears to be conservative because it bounds a great majority of the M5 creepdown data points. The staff considers that the use of the zircaloy-4 creep uncertainties for M5 creep model is conservative and reasonable. Based on the conservative uncertainty and good data fit, the staff concludes that the irradiated creep model for M5 in COPERNIC is acceptable for licensing applications.

6.3 High Stress Creep Model

FCF has also proposed a high stress model for M5 creep in COPERNIC. The main application of this model in the code is to determine stress relaxation when the fuel and cladding are in hard contact. For the situation of hard fuel-cladding contact, the fuel strain determines the total elastic and uniform plastic cladding strain. The high stress creep model is used to determine the rate of stress relaxation and the ratio of plastic to elastic strain. The staff reviewed the model and considered that it is conservative and reasonable. Based on the conservatism, the staff concludes that this model is acceptable for the COPERNIC code.

6.4 Comparison of Code Versus Data

FCF provided several comparisons of code predictions of cladding permanent strain to measured permanent strains from test fuel rods that have been power-ramp tested. However, all but one of these test fuel rods were clad with the older zircaloy-4 material and only one test rod used was clad with the M5 cladding. In addition, these tests involved power ramps that lasted for several hours. This is in contrast to the 1-percent cladding strain analysis performed by FCF, which is intended for anticipated transients that usually last only for a few minutes. The COPERNIC comparison of the predicted permanent strain to the measured strain for the ramped rod with M5 cladding (with a 12 hour hold-time) shows very good agreement. FCF has also provided comparisons of the high stress creep model to permanent strain data from sections of M5 cladding from irradiated fuel rods that were pressure tested at high stresses in out-of-reactor tests. These results are not considered to be integral tests of the code's ability to predict permanent strain in-reactor, but do show that the high stress creep model predicts this data well with a small amount of conservatism.

FCF was asked by the staff whether the comparisons of the COPERNIC predictions to the power ramped rods presented in Sections 6 and 7 of the submittal used the gaseous swelling model in COPERNIC. FCF responded that the gaseous swelling model was used. FCF was further asked by the staff why it was reasonable to use the gaseous swelling model for analyzing the power ramped test rods, but not so to use the gaseous swelling model for the 1-percent strain analysis in anticipated transients. FCF responded that the anticipated transients only lasted a few minutes duration while the test rods in power ramps had hold times of several hours. FCF explained that the gaseous swelling model is important for ramp hold times of several hours, but the kinetics of gaseous swelling is too slow for it to be an important phenomena for transients that last only a few minutes. The staff acknowledges that there is a technical basis for the position that the gaseous swelling kinetics may be slow for anticipated transients, but notes that there is little data to confirm this assertion. Based on the conservative models and satisfactory comparisons between the code and data, the staff concludes that the mechanical models in the COPERNIC code are acceptable for licensing applications.

7.0 LICENSING APPLICATIONS

7.1 Power-to-Melt Analysis

The differences between COPERNIC and FRAPCON-3 fuel thermal conductivity models at high temperatures (> 2000 K) lead to differences in calculated power-to-melt results. Compared to the COPERNIC code at the BOL, the power-to-melt results drop about 5 to 7 percent when the NFI fuel conductivity model from the FRAPCON-3 code is used. Also, due to the lower thermal conductivity burnup degradation of the COPERNIC code, the difference between COPERNIC and FRAPCON-3 with the NFI model increases to about 9 to 10 percent at burnups of 20 to 30 GWd/MTU. The NFI thermal conductivity model compares well with the Ronchi (Reference 6) high-temperature data. FCF noted the trend of reductions in thermal conductivity as burnup increases. FCF believes that the combined effect of the conservatism in the UO_2 fuel melting model and the conservatism in the fuel centerline temperature predictions is enough to offset the effect of the higher thermal conductivity as burnup increases (Reference 22). The staff generally agrees with this finding. In examining the results, the staff considers that the power-to-melt analysis is close to best estimate results at burnups greater than 10 GWd/MTU.

The fuel melting analysis predicts conservative results at BOL, and close to best estimate results when burnups exceed 10 GWd/MTU. Therefore, based on the conservative models and the comparisons with the audit code, the staff concludes that the power-to-melt analysis is acceptable for the COPERNIC code.

7.2 Stored Energy

COPERNIC is used to calculate the initial fuel stored energy for LOCA analyses to verify that fuel designs meet Appendix K requirements. The fuel stored energy is approximately proportional to the fuel volume-average temperature (VAT). Sample COPERNIC "bounding" values for the fuel volume-average temperature as a function of burnup and linear heat generation rate (LHGR) are plotted for the Mark B design (UO2 cycles) in Figure 12-21 of Reference 1. The COPERNIC results show that VATs are at a maximum between rod-average burnups of 30 to 35 GWd/MTU.

The staff requested (Reference 2) and obtained (Reference 3) the power histories and axial power shapes used to make this plot, and repeated the calculations with various thermal conductivity models inserted into FRAPCON-3. The FRAPCON-3 code audit analysis used the same input as used for COPERNIC but used three recently published UO_2 conductivity models (References 4, 5, and 8) to predict VAT. The FRAPCON-3 audit results from all three conductivity models predicted similar values for VAT, and stored energy values that were 10 to 19 percent greater than those predicted by COPERNIC at burnups > 5 GWd/MTU.

The three models used in the FRAPCON-3 were the NFI, Halden, and the EDF models. The NFI thermal conductivity model (Reference 8) has been shown to provide good agreement with Halden high burnup centerline data and ex-reactor measured thermal conductivity data from high burnup fuel published in the open literature (References 9 and 10). The Halden thermal conductivity model is primarily based on Halden measurements of fuel centerline temperatures from high burnup rods. Some of the Halden high burnup rods were irradiated in commercial reactors and then re-fabricated with thermocouples and then irradiated in the Halden reactor. The recently published thermal conductivity model by the French utility EDF is primarily based on ex-reactor measurements of thermal conductivity from high burnup fuel that resulted from the Nuclear Fuel Industry Research (NFIR) program (sponsored by industry) and it should be noted that this model predicts the highest VATs of the three models. The NFIR data has not been published in enough detail that it can be used by PNNL for model verification nor is the detailed data available to the NRC. Therefore, the EDF model is based on a completely independent database from that used to develop the NFI and Halden models, but the data base is not available to PNNL for examination. The databases used to develop the NFI and Halden models are not the same but some of the data used for each overlap. The reason for the higher VATs predicted by the three recent thermal conductivity models is that they show a stronger degradation in thermal conductivity with increasing burnups.

Because the FCF VAT plots in the submittal show VAT increasing with burnup, the staff asked an additional question about whether LOCA peak clad temperatures (PCTs) remain limiting at BOL for FCF fuel (Reference 20). FCF responded (Reference 21) that this will be determined when the COPERNIC code is approved and then the LHGR limits for LOCA will be determined accordingly. FCF further stated that for Westinghouse and Combustion Engineering plants, the local peaking factor is restricted so that BOL PCTs remain limiting. However, a new LHGR limit may be required for these plants when the COPERNIC code is used. COPERNIC and FRAPCON-3 audit code calculations both show that the maximum stored energy is no longer greatest at BOL but is greatest at mid-life burnups of about 30 to 35 GWd/MTU. This is important because most approvals for fuel performance audit codes in the past have been based on calculations that show LOCA PCTs are greatest at BOL where fuel rod properties beyond BOL do not have to be considered.

In addition, FCF has proposed in their response (Reference 22) that they reduce the hold-time of the power transient (they currently use a 12 hour hold-time) used to initialize the LOCA stored energy and rod pressures. They propose to use the plant specific technical specification that limits the amount of time (typically in the range of 15 minutes to 4 hours) that the fuel can operate in excess of the specified acceptable fuel design limits for the power transient hold-times used to initialize LOCA conditions.

The 12 hour hold-time is a legacy from the original approval of the TACO3 fuel performance code (Reference 24). The TACO3 code required a long hold-time because the FGR model in this code did not adequately predict FGR for short time transients, but adequately predicted FGR for steady-state power operation. Consequently, the application of the TACO3 code to transient power conditions required long hold-times for the code to allow for equilibrium FGR to be achieved. The COPERNIC code appears to adequately predict FGR during power transients. Therefore, it is not necessary to continue the practice of using abnormally long hold-times for accident initiation unless justified for the accident type. The staff concludes that the use of technical specification limits to determine the amount of hold-time for LOCA initial conditions is acceptable for the COPERNIC code.

Based on the consistent results with the audit code and the conservative models, the staff concludes that the stored energy analysis for LOCA initial conditions is acceptable for the COPERNIC code.

7.3 Fuel Rod Internal Pressure

FCF provided an example of the COPERNIC results from a fuel rod internal pressure analysis of the Mark B design. An audit calculation was performed with FRAPCON-3 using the same input, and the results showed that FRAPCON-3 predicted slightly greater pressures than COPERNIC except near the end-of-life, where the two predictions were nearly identical. This is considered acceptable because most fuel today is licensed for rod-average burnups greater than 55 GWd/MTU where the two codes predict similar results. The staff concludes that the COPERNIC code is acceptable for application to fuel rod pressure analyses.

7.4 Clad Strain

Section 4.2 of the Standard Review Plan (SRP) suggests a 1 percent strain limit (elastic plus uniform plastic) for normal and anticipated transient fuel operation (Reference 23). In general, anticipated transients provide the greatest prediction of clad strain, and are therefore used for the1 percent strain analysis. FCF provided examples of COPERNIC calculated power limits for their clad strain analysis of the Mark B design as a function of burnup results in Figure 12-28 (Reference 1). An audit calculation was performed by the staff with FRAPCON-3 using the same input. A comparison of the COPERNIC and FRAPCON-3 results shows that the two codes are generally in good agreement. This small difference makes it difficult for assessing the ability of either code in performing these calculations because of the lack of in-reactor measured strain data for the relatively fast power ramps (on the order of a few minutes) assumed for this analysis.

Based on its use of conservative models and good agreement with the NRC audit code which predict results that are conservative compared to the staff's independent analysis, the staff concludes that the cladding strain analysis is acceptable for the COPERNIC code.

8.0 CONCLUSIONS

The staff has reviewed FCF's improved fuel performance code, COPERNIC, for the advanced cladding M5 for fuel rod mechanical designs described in BAW-10231P. The staff concludes that the COPERNIC code is acceptable for fuel licensing applications up to a rod average burnup of 62 Gwd/MTU.

Licensees that reference this topical report still need to meet 10 CFR 51.52, "Environmental effects of transportation of fuel and waste"-Table S-4.

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