UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

REVISED SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10227P

"EVALUATION OF ADVANCED CLADDING AND STRUCTURAL MATERIAL (M5)

IN PWR REACTOR FUEL"

FRAMATOME COGEMA FUELS, INC.

1.0 INTRODUCTION

Framatome Cogema Fuels (FCF) has submitted to the U.S. Nuclear Regulatory Commission (NRC) a topical report entitled "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," BAW-10227P (Reference 1), for review and approval. This report provides the licensing basis for the FCF advanced cladding and structural material, designated M5, and requests full batch implementation of this material for their Mark-B (15X15 fuel array) fuel design for B&W type reactors, and Mark-BW (15X15 and 17X17 fuel arrays) designs for Westinghouse type reactors. This submittal further requests full batch implementation of this material up to the currently approved rod-average burnup level of 62 GWd/MTU for the Mark B design and 60 GWd/MTU for Mark BW designs (Reference 2).

It should be explained that Framatome Cogema Fuels was previously named the B&W Fuel Company (BWFC), a part of B&W Nuclear Technologies, and prior to BWFC was named Babcock & Wilcox (B&W). Some of the references in this safety evaluation (SE) refer to these different company names depending on the date the reference was generated.

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC in this review. As a result of the NRC staff's and their PNNL consultants' review of the topical report, the NRC sent a two-part list of questions to FCF. The first part (Reference 3) addressed Sections 1 through 6 and Appendices A and B of the report that discussed M5 properties and models generally associated with normal operation. The second list of questions (Reference 4) addressed Appendices C, D, E, and G of the report that discussed cladding rupture, ballooning, flow blockage, and high temperature oxidation models used in loss-of-coolant accident (LOCA) analyses. Both sets of questions (References 3 and 4) requested additional data that support the M5 material property and cladding performance models, additional information about the data provided, assumptions used in model development, and to provide example licensing analyses. FCF partially responded to the first list of questions in Reference 5 and provided the remaining responses to the second list in Reference 6. FCF submitted a revised M5 creep model in Reference 7. FCF also supplied additional information (Reference 8) to support their responses to questions for some of the original request for additional information (RAI). In Reference 9, FCF supplied information on their new axial growth methodology and a commitment to obtain additional M5 data up to currently approved burnup levels.

This report consists of nine sections, Section 1 - Introduction, Section 2 - M5 Material Properties, Section 3 - Fuel System Damage, Section 4 - Fuel Rod Failure, Section 5 - Fuel Coolability, Section 6 - Fuel Surveillance, Section 7- M5 LOCA Evaluation, Section 8 - Conclusions, and Section 9 - References. Section 2, as the title implies, addresses the M5 material properties, while Sections 3, 4, 5, 6, and 7 address licensing requirements identified in Section 4.2 of the Standard Review Plan (SRP) (Reference 10) for fuel designs. Some of the licensing requirements identified in Section 4.2 of the SRP require fuel performance properties or models be used to demonstrate that design criteria or limits are met. Therefore, subsections of Section 2 will refer to Sections 3, 4, 5, 6, and 7 and vice versa.

Section 4.2 of the SRP states that fuel system safety review must provide assurance that (1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), (2) fuel system damage is never so severe as to prevent control rod insertion when it is required, (3) the number of fuel rod failures is not underestimated for postulated accidents, and (4) coolability is always maintained. A "not damaged" fuel system is defined as fuel rods that do not fail, fuel system dimensions that remain within operational tolerances, and functional capabilities that are not reduced below those assumed in the safety analysis. Objective 1, above, is consistent with General Design Criterion (GDC) 10 (10 CFR Part 50, Appendix A) (Reference 11), and the design limits that accomplish this are called specified acceptable fuel design limits (SAFDLs). "Fuel rod failure" means that the fuel rod leaks and that the first fission product barrier (the cladding) has, therefore, been breached. However, the staff recognizes that it is not possible to avoid all fuel rod failures during normal operation, and reactor coolant cleanup systems are installed to deal with a small number of leaking rods. Fuel rod failures must be accounted for in the dose analysis required by 10 CFR Part 100 (Reference 12) for postulated accidents. "Coolable geometry" means, in general, that the fuel assembly retains its rod-bundle geometrical configuration with adequate coolant channels to permit removal of residual heat for a design-basis accident. The general requirements to maintain control rod insertability and core coolability appear repeatedly in the GDC (e.g., GDC 27 and 35). Specific coolability requirements for the LOCA are given in 10 CFR Part 50, Section 50.46 (Reference 13).

In order to assure that the above stated objectives are met, and to follow the format of Section 4.2 of the SRP, Sections 3, 4, and 5 of this SE cover the following three major categories: (1) fuel system damage mechanisms, which are most applicable to normal operation and AOOs, (2) fuel rod failure mechanisms, which apply to normal operation, AOOs, and postulated accidents, and (3) fuel coolability, which are applied to postulated accidents. Specific fuel damage or failure mechanisms are identified under each of these categories in Section 4.2 of the SRP. This SE discusses, under each fuel damage or failure mechanism listed in the SRP, the FCF design limits, analysis methods and data used to demonstrate that the SAFDLs are met up to the rod-average burnup levels of 62 GWd/MTU for Mark B and 60 GWd/MTU for Mark BW designs.

The purpose of the FCF design criteria or limits (defined in Reference 14) is to provide limiting values that prevent fuel damage or failure and fuel coolability/control rod insertability for postulated accidents with respect to each mechanism. The FCF design criteria remain the same as defined in Reference 14 for fuel designs with the M5 alloy. The staff reviewed whether FCF has adequate data to demonstrate that fuel designs using M5 cladding and structural material can operate satisfactorily up to rod-average burnups of 62 GWd/MTU for Mark B and 60 GWd/MTU for Mark BW designs as defined by the SAFDLs for normal operation, AOOs and postulated accidents.

Section 7.0 of this SE addresses the changes to the emergency core cooling system (ECCS) evaluation models to account for M5 cladding. This section covers calculated results, sensitivities, and compliance with 10 CFR 50.46.

2.0 M5 MATERIAL PROPERTIES

The M5 material properties addressed in this section are in general, applicable to properties under normal operation and AOOs, but some such as fuel thermal conductivity, thermal expansion, heat capacity, α→β phase transformation, and emissivity up to fuel melting are also applicable to design basis accidents. Other properties that are unique to accident conditions, such as cladding rupture, ballooning, flow blockage, and high temperature oxidation, are addressed in Sections 4 and 5 of this SE. The properties addressed in this section, along with FCF analysis methodology, are used to demonstrate that FCF fuel designs meet the SAFDLs defined in Sections 3, 4, and 5 of this SE.

2.1 Specific Gravity (Density)

The FCF value for specific gravity of the M5 alloy is interpolated from the measured values reported for pure reactor grade zirconium and that reported for the zirconium - 2.5 percent niobium alloy. The specific gravity for these two materials are within 10 percent of each other and, therefore, little change in specific gravity is expected. In addition, a 1 or 2 percent error in the specific gravity will not impact fuel performance analyses and, therefore, the interpolated values are satisfactory. The NRC staff concludes that the FCF value for M5 specific gravity is acceptable for M5 licensing applications up to currently approved burnup levels.

2.2 Coefficient of Thermal Expansion

FCF has proposed (Reference 6) a different coefficient of thermal expansion for M5 cladding than presented in the original submittal (Reference 1) based on new FCF dilatometry measurements in the radial, azimuthal, and axial directions with a reference point of 20°C (Reference 8). These results demonstrate that there is a small difference from Zr-4 and a larger difference in contraction in the α+β phase region. The α+β region is the phase transition region where both α and β phases are present, while α→β represents the α to β phase transformation process. Due to the contraction in the α+β phase region there is a significant change in slope of the expansion coefficient in this region that once again changes to a more positive slope when the β phase transition is complete. Examination of the FCF data and correlations for M5 expansion demonstrates that the M5 correlation for expansion in the α and β phase regions matches the data very well, but the transition point between the α phase and the α+β phase is not consistent with the new revised FCF α→β phase transformation temperatures (see Section 2.17 of this SE). The FCF correlation for M5 thermal expansion shows the α→β phase transition beginning at a temperature approximately 60°C before the new proposed FCF phase transformation temperature for the start of the α→β phase region. The M5 expansion model cannot be correct if the FCF α→β phase transformation temperature is correct.

This is not a problem for fuel performance analyses at normal cladding operating temperatures but is an issue for transients that achieve high cladding temperatures such as for LOCA, i.e., that reach the $\alpha \rightarrow \beta$ phase transformation temperatures.

The staff asked FCF about this inconsistency and what the impact would be on LOCA analyses, based on the current FCF assumption that the cladding contracts 60°C below the actual point of contraction. FCF responded that this would have a very small impact on the LOCA analyses because this will only change the gap size by a very small amount and in turn the gap conductance by a very small amount. The NRC staff agrees that the impact on LOCA analyses is small.

The NRC staff concludes that the FCF correlation for M5 thermal expansion (Reference 6) is acceptable for M5 licensing applications up to currently approved burnup levels.

2.3 Thermal Conductivity

The thermal conductivity relationship submitted in Reference 1 was modified in the first response to questions (Reference 5) because additional data became available. However, Reference 5 did not provide the data used for supporting the new modified thermal conductivity relationship. The staff asked FCF to supply this new data, and FCF provided it in Reference 8. The FCF data demonstrated that the modified relationship given in References 5 and 8 was a satisfactory representation of measured M5 thermal conductivity similar to the relationship used for Zircalloy-4 (Zr-4). Therefore, the NRC staff concludes that the modified thermal conductivity relationship in References 5 and 8 is acceptable for M5 licensing applications up to currently approved burnup levels.

2.4 Heat Capacity

The heat capacity relationship submitted in Reference 1 was modified in Reference 6 based on proprietary data from Commissariat a l'Energie Atomique (CEA) testing in the α and β region for M5 material, and Russian open literature data (References 15, 16, and 17) from material similar to M5. The FCF correlation for heat capacity in the α region is based on the average of the Russian and CEA data. The FCF correlation for heat capacity in the β region is based on combining the average of the Russian data with the average of the CEA data. The average of the two data sets were used to determine the mean heat capacity in the β region in order to provide equal weighting between the two data sources (CEA and Russian).

The heat capacity in the $\alpha+\beta$ region was determined from the CEA measured data in this temperature range. The uncertainty in M5 heat capacity in these three temperature ranges is approximately 8 percent. Since the uncertainty in M5 heat capacity is considered in the safety analyses, the NRC staff concludes that the FCF heat capacity correlations for M5 are acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

2.5 Emissivity

The emissivity for M5 does not change much within the temperature range of interest for LOCA and safety analyses and, therefore, is represented as a constant value, as is currently the case for Zr-4. Reference 1 stated there was little difference between Zr-4 and M5 emissivity. However, Reference 6 states that the emissivity value for M5 material is larger than for Zr-4 based on recent data. The staff examined the data and found the new M5 emissivity value to be a satisfactory representation of M5 emissivity, which varies a small amount within the temperature range of application. Because cladding radiation heat transfer is not a dominant mechanism for a fuel rod and the variation of emissivity within the range of application is small, the use of the FCF constant value of cladding emissivity on LOCA and safety analyses is acceptable. The NRC staff concludes that the Reference 6 value for emissivity is acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.6 Oxidation

The M5 application that results in the most severe oxidation environment for both normal operation and accident operation is the fuel cladding. Cladding oxidation for normal operation and LOCA is discussed in Sections 3.4 and 5.1, respectively.

2.7 Ultimate Tensile Strength

The ultimate tensile strength (UTS) is used by FCF to determine the stress intensity limits for the assembly guide thimbles for seismic-LOCA and other assembly loading analyses based on guidelines established in Section III of the American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code (Reference 18). FCF was asked to provide the M5 UTS correlation with temperature used for licensing analyses and a comparison to data. These were provided in Reference 8 and demonstrated that the M5 axial UTS correlation conservatively bounds the unirradiated M5 data. The M5 UTS increases significantly (a factor of 1.4 to 1.9) and quickly with burnup (less than 10 GWd/MTU) compared to the unirradiated values. The use of unirradiated M5 UTS offers additional conservatism in FCF analyses. The NRC staff concludes that the FCF unirradiated UTS bounding correlation is conservative and, therefore, acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.8 Yield Strength (0.2 Percent Offset)

The Reference 1 model for predicting M5 yield strength (0.2 percent offset) is based on unirradiated cladding data and was found to overpredict the unirradiated M5 data by up to 10 percent within given temperature ranges used for FCF analyses. A new yield strength model, provided in Reference 8, was found to be in much better agreement with, or conservative with relation to, the unirradiated M5 yield strength data. In general, the use of unirradiated values for yield strength is conservative for determining the cladding stress limits that are discussed in Sections 3.1 and 5.4 of this SE. This is because yield stress values for recrystalized zirconium base alloys increase by nearly a factor of 2 or greater following short term irradiation. FCF has provided measurements of M5 yield strength as a function of burnup that demonstrates it increases by a factor of 3 or more compared to unirradiated values within less than 10 GWd/MTU burnup. It is concluded that the FCF model for unirradiated yield strength is very conservative for determining in-reactor M5 strength. The NRC staff concludes that the FCF unirradiated yield strength correlation is acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.9 Ductiltity

Cladding ductility needs to be retained to avoid brittle failures. Generally, irradiation and hydride formation (due to corrosion) have been found to decrease the ductility of zirconium alloys (References 19, 20, and 21). The NRC does not have a specific minimum limit on cladding ductility; however, Section 4.2 of the SRP (Reference 10) suggests a limit for total (elastic + plastic) cladding uniform strain of 1 percent that should not be exceeded during normal operation and AOOs. Therefore, the SRP would suggest a minimum total strain capability of at least 1 percent in order to prevent cladding failure below the 1 percent strain limit.

FCF was asked (Reference 3) to supply measured strains from tensile and burst tests of both unirradiated and irradiated M5 cladding. FCF supplied (Reference 5) the requested data for unirradiated cladding and cladding that was irradiated to fuel rod burnups of 10, 20, and 38 GWd/MTU. The tensile data demonstrated reasonably high strains compared to Zr-4 strain data. The biaxial burst test data demonstrated that uniform plastic strains were below 1 percent for the irradiated M5 cladding with only one data point for total elongation strain and this datum was above 1 percent strain. The uniform strains from both the tensile and biaxial tests do not appear to decrease with increasing burnup but appeared to be uniform within the burnup range of the data, i.e., 10 to 38 GWd/MTU. In addition, further M5 burst strain data have recently been obtained by FCF at a rod-average burnup of 43 GWd/MTU that is consistent with the lower burnup FCF strain data for M5. This suggests that there is no further decrease in ductility with burnup within the range of the FCF data for M5. The M5 uniform strains from the biaxial tests are on average lower than those observed on similar Zr-4 test specimens at similar burnup levels but they are within the lower bounds of the Zr-4 data. In addition, the biaxial ultimate tensile strengths for the irradiated cladding were only slightly higher than the measured yield strengths indicating that total strains were low. The staff asked FCF why total elongation strain was measured on only one irradiated burst test specimen, and also asked FCF to provide micrographs of the fracture surfaces at high magnification to demonstrate ductility in the failure location. FCF responded that they had difficulty in measuring total strains on these burst specimens and did not have any high magnifications of the failure surfaces of these specimens.

FCF noted that the burst tests of the M5 cladding demonstrated total (elastic + plastic) uniform strain capability greater than 1 percent using the measured yield strengths for this data and, therefore, M5 meets the 1 percent strain limit suggested in the SRP. The NRC staff confirmed that the M5 burst test specimens met the 1 percent (elastic + plastic) strain limit by a small margin.

FCF was also asked (Reference 3) to supply in-reactor power ramp test data (including total measured strains) from irradiated rods with M5 cladding. FCF responded that they had performed 5 ramp tests (rods with burnups between 25 to 30 GWd/MTU) with some rods resulting in failure and others remaining intact. The failure threshold in terms of rod powers and delta power change for these rods were found to be similar to those observed for FCF Zr-4 fuel rods. The plastic strains for the failed rods with M5 cladding were below 1 percent strain but the total (elastic + plastic) calculated strains remained above 1 percent. It is noted that low strains are also seen in power ramp tested Zr-4 rods because the cesium and iodine released during these power ramps promote cracking of the cladding on the inside surface. FCF was also asked to supply micrographs of the failure surfaces of the ramped rods as well. These micrographs were supplied and demonstrated a crack surface at the cladding inner-diameter but then quickly transformed to ductile cupping for the failure surface. This indicates that the irradiated M5 cladding remained ductile outside of the inner diameter (ID) surface.

The NRC staff concludes that the M5 cladding meets the 1 percent strain criterion of SRP Section 4.2, and remains ductile up to the burnup range of current data (43 GWd/MTU), but notes that FCF needs to collect M5 tensile and burst test data (including uniform strain, total strain, and micrographs of the fracture surfaces at high magnification) up to currently approved burnup levels of 60 and 62 GWd/MTU for FCF designs. FCF has committed to collecting this data up to currently approved burnup levels (see Section 6, FUEL SURVEILLANCE). FCF has further committed to inform the NRC if they find either of the following in these M5 mechanical tests; (1) total (elastic + plastic) uniform strains falling below 1 percent, or (2) the micrographs showing brittle failure surfaces (Reference 9).

The NRC staff concludes that the M5 alloy has acceptable ductility for fuel rod strain licensing analyses of M5 cladding up to currently approved burnup levels based on FCFs commitment to collect further M5 strain data up to approved burnup levels.

2.10 Creep

In Reference 1, FCF proposed using their old Zr-4 creep model with an adjustment multiplication factor (less than 1.0) for determining M5 material creep, with the M5 material showing lower overall creep than Zr-4. It is noted that the M5 creep data is currently only from 4 irradiated rods from one plant and further creep data are planned from future fuel exams of lead test assemblies (LTAs). FCF will use this revised Zr-4 creep model for determining M5 creep in their current fuel performance code, TACO-3 (Reference 22). TACO-3 code comparisons of predicted creep to the M5 creep data demonstrates a significant scatter in the data but is considered to be a satisfactory comparison for its intended application in TACO-3. Therefore, the modified Zr-4 model (with an adjustment factor) to predict the M5 cladding creep is considered to be satisfactory for fuel performance calculations in TACO-3. It is noted that FCF has recently submitted a new fuel performance code for NRC review that may have a more sophisticated M5 creep model.

For creep collapse analysis, FCF proposed (Reference 1) to continue to use their Zr-4 creep model for creep collapse (with no adjustment factors, e.g., a multiplication factor of 1.0) because they believed that this model would remain conservative for this application. However, FCF developed a new M5 creep model that was submitted in Reference 7. FCF discovered that the Zr-4 creep model was slightly less conservative than the new M5 creep model at moderate-to-high burnup levels for determining rod internal pressure limits (no fuel cladding gap reopening is allowed) and for cladding collapse analyses. The greater predicted creep in M5 at high burnups is due to the fact that the M5 creep data shows a smaller amount of in-reactor primary creep (transient) resulting in a larger secondary (steady-state) creep rate, proportionately, than observed for their standard Zr-4 creep data and model. The secondary creep rate is important for both determining the FCF rod pressure limits (based on the limit for gap reopening) and cladding collapse for their fuel designs at high burnup levels. The new M5 creep model conservatively ignores primary creep by assuming that all the creep observed is secondary creep. This will typically result in an underprediction of cladding creep data early-in-life and an overprediction later-in-life which is conservative for determining the rod pressure limit and cladding collapse at high burnup levels. This new M5 creep model has been compared to the M5 creep data from the 4 irradiated rods and found to provide a small underprediction of the first cycle data (from two rods) and a larger overprediction of the second cycle data that demonstrates the conservatism in the M5 creep model at higher burnup levels. In addition, there were two creep data from two third cycle rods (measured at the fuel rod ends where the gap has not closed) that were significantly overpredicted by the new M5 model that further demonstrates the conservatism in the M5 creep model.

The standard error for this new M5 model was significantly smaller than the standard error for Zr-4 creep model, but the Zr-4 model was based on a much larger data base with rods from several different reactors. The standard error for the new M5 creep model is also significantly smaller than that for the Zr-4 model modified for M5 based on the limited M5 data. However, due to the small amount of M5 cladding creep data from which their new M5 creep model is based, FCF intends to continue to use the more conservative standard error based on the Zr-4 creep model and standard Zr-4 creep data for determining the upper bound uncertainty in M5 creep. FCF's conservative assumptions of no primary creep in their new M5 creep model and the use of the standard error from the standard Zr-4 model offers sufficient conservatisms for calculating the FCF rod pressure limits and cladding collapse. The previous approval of FCF's rod pressure analysis methodology (Reference 23) concluded that the conservatisms in the FCF fuel swelling model plus those in the creep model were sufficient to compensate for the potential difference between compressive versus tensile creep that has been proposed by others (References 24 and 25).

The NRC staff concludes that the use of the modified Zr-4 creep model (multiplication factor for M5) for modeling M5 creep in TACO-3 is acceptable for licensing applications with M5 cladding up to currently approved burnup levels. The NRC staff further concludes that the use of the new M5 creep model (Reference 7) and uncertainites (i.e, the uncertainties of the M5 model are assumed to be the same as those from the Zr-4 model and data) are acceptable for determining rod pressure limits (see Section 3.8 of this SE) and for cladding collapse (see Section 4.2 of this SE) licensing analyses with M5 cladding up to currently approved burnup levels.

2.11 Poisson's Ratio

FCF uses a constant value for Poisson's ratio with temperature that is consistent with the value used for Zr-4. The FCF constant value for Poisson's ratio has been compared to data for M5 and a similar Zr-1 percent Nb alloy and shown to agree well with this data (Reference 6). The NRC staff concludes that FCF's value of Poisson's ratio for M5 is acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.12 Modulus of Elasticity

In Reference 1, FCF proposed that the Zircaloy correlations for modulus of elasticity used in RELAP5 (Reference 26) and TACO-3 (Reference 22) be used for the M5 alloy. The difference in elastic modulus between Zircaloy and M5 materials is expected to be similar. However, FCF submitted a new correlation for M5 modulus of elasticity in References 5 and 8 with measured data up to 350 °C. This new M5 correlation is intended to be used in both the RELAP5 and TACO-3 codes, where the former is used for accident analyses (LOCA) and the latter for analyses related to normal operation and AOOs.

PNNL's comparison between FCF's correlation to that recommended in MATPRO-11 (Reference 27) for Zr-4 demonstrated very good agreement up to 400 °C and then started to become slightly larger with a higher value at 1000 °C than the MATPRO Zircaloy correlation. This higher value is within the scatter of the data for Zircalloy's modulus of elasticity and is considered to be acceptable. In addition, for the maximum temperatures used for LOCA analyses, the elastic strains are small compared to either thermal expansion strains in the 700°C to 1000°C range or strain due to plastic deformation in the 1000°C to 1200°C range. Therefore, a small variation in modulus of elasticity has a negligible impact on LOCA analysis results. The impact of the modulus of elasticity is of greater significance at normal operating reactor temperatures; in this region the M5 modulus of elasticity is nearly identical to the MATPRO Zircaloy correlation. The NRC staff concludes that the M5 modulus of elasticity correlation proposed in References 5 and 8 is acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.13 Hardness (Meyer's)

Meyer hardness is used in calculating the contact conductance between the fuel and cladding when the fuel-to-cladding gap is closed. FCF utilizes the MATPRO-11 (Reference 27) correlation for Zircaloy-4 Meyer hardness for the M5 alloy. Generally, the Meyer hardness of an alloy is related to the yield strength of the alloy. The M5 alloy has a significantly lower unirradiated yield strength than Zr-4 but hardens quickly with irradiation. The M5 irradiated yield strength in the tensile direction is nearly 70 percent of that for irradiated Zr-4 and similar to Zr-4 for the biaxial pressure tests. Therefore, the Meyer hardness for irradiated M5 cladding is most likely a little lower than for irradiated Zr-4 cladding. The consequence of having an overprediction of Meyer hardness for M5 cladding would be a lower contact conductance and higher fuel temperatures. For those analyses where contact conductance occurs higher fuel temperatures result in more conservative results. The NRC staff concludes that the FCF correlation for Meyer hardness is conservative and, therefore, acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.14 Growth

Generally both fuel assembly and fuel rod growth have been shown to be linear with fast fluence (E> 1 mev) for Zr-4 and Zr-2 alloys and similar behavior is expected for the M5 alloy; however, as noted below the M5 fuel rod growth appears to saturate at high fluences (greater than 8 x 10^{21} n/cm^2) based on a limited data base.

M5 guide tube/thimble (assembly) growth needs to be evaluated to prevent the assembly holddown springs from bottoming out that would result in assembly and fuel rod bowing (see Section 3.7 of this SE). FCF has presented upper tolerance and lower tolerance limits (UTL and LTL, respectively) for both Zr-4 and M5 assembly (guide tube/thimble) growth. FCF has over 80 assembly measurements of assembly growth with Zr-4 guide tubes for assembly burnups up to 58 GWd/MTU. Currently, FCF has only two data points for M5 guide tube growth at an assembly burnup of 22 GWd/MTU. The UTL curve for M5 assembly growth is very conservative compared to the two data points while the LTL curve is adequately conservative. FCF has committed to collecting further assembly growth data for M5 guide tubes in North Anna up to currently approved burnup levels (see Section 6, FUEL SURVEILLANCE). The NRC staff concludes that the M5 guide tube/thimble (assembly) growth model is acceptable for licensing applications with M5 guide tubes/thimbles up to currently approved burnup levels based on FCFs commitment to collect further M5 assembly growth data up to approved burnup levels. M5 cladding irradiation axial growth needs to be considered in the TACO 3 fuel performance code (Reference 22). FCF presented a correlation for rod growth as a function of burnup with upper and lower bounds along with measured rod growth data up to a fluence of approximately 10 x 10^{21} n/cm^2 (E> 1 MeV) (this fluence translates to a burnup of approximately 52 GWd/MTU). Another datum point with a fluence of 11.8 x 10^{21} n/cm^2 (burnup of 61 GWd/MTU), which was added to this rod growth data in Reference 5, lies significantly below the mean of the M5 growth curve. Based on the limited amount of data (7 to 9 data) to date above a fast fluence of 8 x 10^{21} n/cm^2 there appears to be a saturation in the M5 growth. This would suggest that FCF's upper bound for axial growth is indeed bounding up to 61 GWd/MTU. The NRC staff concludes that the M5 fuel rod (cladding) growth model is acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

2.15 Hydrogen Pickup Fraction

In Reference 1, FCF provided a hydrogen pickup fraction that was more than a factor of 2 lower than that observed in Zr-4; however, the data only extended to a burnup of 38 GWd/MTU (with less than 20μm of oxide thickness) and showed a higher fraction at burnups greater than 20 GWd/MTU. FCF was asked (Reference 3) about the higher pickup fraction in the data at burnups greater than 20 GWd/MTU than the FCF assumed value in Reference 1. FCF responded (Reference 5) that the Reference 1 pickup fraction was based on early results of pickup fraction, and in Reference 5 FCF revised the pickup fraction upwards to a larger value, but was still considerably lower than the fraction measured for Zr-4 (0.15, Reference 28). The data in References 27 and 28 for Zr-4 demonstrated that the hydrogen pickup fraction continued to increase with increasing oxide thickness (and burnup) until a thickness between 50 and 60μm was achieved. The hydrogen pickup fraction for the M5 alloy may be lower than that observed for Zr-4, but based on past experience with Zr-4 the pickup fraction will increase with increasing oxide thickness until a thickness between 50 to 60μm is achieved. Currently, FCF has measured hydrogen content on cladding with only oxide thicknesses (less than 20μm). Considering the lack of data beyond 35 GWd/MTU, the NRC staff recommended that FCF continue collecting data and use a pickup fraction of 0.10, which is close to the maximum M5 pickup fraction, to compensate for the burnup effect. Based on FCF's commitment to collect further hydrogen pickup fraction data up to approved burnup levels (see Section 6, FUEL SURVEILLANCE), the NRC staff concludes that the hydrogen pickup fraction is acceptable for use in licensing applications (see Section 4.1) with M5 cladding up to currently approved burnup levels.

2.16 Stress Corrosion Cracking

The NRC currently has no requirements related to stress corrosion cracking (SCC) of fuel assembly components other than the total uniform 1 percent strain limit discussed in Section 2.2 of this SE. However, FCF has performed SCC sensitivity testing on M5 and compared it to their Zr-4 material. The tests were out-of-reactor ring tensile tests with nearly constant strain rate on unirradiated cladding in a mixture of argon gas and iodine vapor. These tests demonstrated that the M5 alloy was less susceptible to SCC (higher ductility) than their standard Zr-4 alloy.

2.17 $\alpha \rightarrow \beta$ Phase Transformation Temperatures

The $\alpha \rightarrow \beta$ transformation temperatures are not listed by FCF as a separate material property for the M5 alloy. The transformation temperatures have been singled out in this review because of their importance in interpreting some M5 material properties (because these properties change during and following the transformation to the β phase) and behavior. Some of the M5 material properties that change are thermal expansion, heat capacity, rupture and ballooning. Therefore, it is important to know the temperature range of this phase transformation.

The NRC staff asked FCF about the $\alpha \rightarrow \beta$ phase transformation temperatures provided in their original submittal (Reference 1), and the data from which the initiation and the completion of the transformation temperatures were obtained, because the phase change started at a lower temperature and completed at a higher temperature than had been previously observed for similar zirconium alloys. FCF responded (Reference 5) that they had since obtained better test data of the $\alpha \rightarrow \beta$ transformation temperatures, and provided the new phase transformation temperatures, the data and testing methods. The newly revised FCF transformation temperatures agreed very well with other NRC proprietary information on similar zirconium alloys. The FCF test data also suggested that the initial transformation and completion of the transformation temperatures were dependent on the heating rate, i.e., the kinetics of the phase transformation impact the transformation temperatures. This shift to higher transformation temperatures is also observed in their cladding ballooning (strain) data and models (see Section 5.3). The NRC staff asked FCF about whether this should be explicitly modeled (currently it is implicitly modeled for LOCA ballooning because the effect is inherent in the data). FCF stated that while the data qualitatively demonstrates a kinetic effect on the transformation temperature, FCF currently does not have sufficient data to model the kinetics quantitatively. The NRC staff agrees with FCF's assessment of the data and modeling capabilities.

The NRC staff concludes that the FCF $\alpha \rightarrow \beta$ transformation temperatures are acceptable for use in licensing applications with M5 cladding up to currently approved burnup levels.

3.0 FUEL SYSTEM DAMAGE

The design criteria presented in this section should not be exceeded during normal operation including AOOs. The evaluation portion of each damage mechanism evaluates the analysis methods and analyses used by FCF to demonstrate that the design criteria are not exceeded during normal operation, including AOOs, for their Mark-B and Mark-BW designs.

3.1 Stress

Bases/Criteria - In keeping with the GDC 10 SAFDLs, fuel damage criteria for cladding stress should ensure that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis. The FCF design criteria for fuel rod cladding and assembly stresses are based on unirradiated yield and ultimate tensile strengths to determine the stress limits for all M5 applications. The M5 yield and ultimate tensile strengths are discussed in Sections 2.7 and 2.8 of this SE and found to be acceptable. The use of unirradiated values is conservative because irradiation has been shown to increase the yield and ultimate tensile strengths for M5 and other zirconium alloys. These criteria are consistent with the acceptance criteria established in Section 4.2 of the SRP and have been previously approved in Reference 14. The NRC staff concludes that these stress criteria are acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - The stress analyses for FCF fuel assembly components and fuel rod cladding are based on standard stress analysis methods including finite-element analysis. FCF will utilize the same analysis methods for M5 material as previously used and approved for Zr-4 (Reference 14). Pressure and temperature inputs to the stress analyses are chosen so that the operating conditions for all normal operation and AOOs are enveloped. The cladding wall thicknesses are reduced to those minimum values allowed by fabrication specifications and further reduced to allow for corrosion on the inside and outside diameter. FCF uses the cladding corrosion from COROSO2 (see Section 3.5) to determine corrosion on the outside diameter. The NRC staff concludes that the FCF design analysis methods for stress analyses for M5 materials are consistent with the guidelines in Section 4.2 of the SRP and are acceptable for licensing applications with M5 cladding up to currently approved burnup levels.

3.2 Strain

Bases/Criteria - The FCF design criteria for fuel rod cladding strain is that the maximum uniform hoop strain (elastic plus plastic) shall not exceed 1 percent. This criteria is intended to preclude excessive cladding deformation from normal operation and AOOs. This is the same criterion for cladding strain that is used in Section 4.2 of the SRP and has previously been approved in Reference 14.

The material property that could have a significant impact on the cladding strain limit is cladding ductility. The strain criterion could be impacted if cladding ductility were decreased, as a result of in-reactor operation, to levels that would allow cladding failure without the 1 percent cladding strain criteria being exceeded under normal operation and AOOs.

As noted in Section 2.9 of this SE, FCF has collected ductility data from irradiated M5 cladding with burnups up to 43 GWd/MTU. These data demonstrate that M5 ductility exceeds the 1 percent total (elastic + plastic) uniform strain requirement and, therefore, has adequate ductility. In addition, FCF has committed to collecting additional M5 ductility data up to currently approved burnup levels (see Section 6.0). The NRC staff concludes that FCF's 1 percent strain criterion is applicable to M5 cladding up to currently approved burnup levels based on FCF's commitment to continue to collect M5 ductility data up to approved burnup levels.

Evaluation - Reference 1 stated that the TACO-3 fuel performance code (Reference 22) is used for cladding strain analyses. FCF uses conservative bounding values for input to TACO-3 for this calculation including worst case fabrication tolerances, pressure differentials and power histories (including AOOs). Total strain as calculated by TACO-3 is strictly a function of fuel expansion and is not dependent on yield or ultimate tensile strength and, therefore, the use of M5 cladding is not expected to have a significant impact on cladding strain analyses. FCF was asked to provide an example 1 percent strain analysis with M5 cladding properties. FCF provided the results of an example strain analyses in Reference 5 for both M5 and Zr-4 cladding properties that demonstrated nearly identical results. This fuel performance code has been previously reviewed and approved by NRC up to a rod-average burnup of 62 GWd/MTU. The NRC staff concludes that the FCF analysis methodology for 1 percent cladding strain is applicable to M5 cladding up to currently approved burnup levels.

3.3 Strain Fatigue

Bases/Criteria - The FCF design criterion for cladding strain fatigue is that the cumulative fatigue usage factor be less than 0.9 when a minimum safety factor of 2 on the stress amplitude or a minimum safety factor of 20 on the number of cycles, whichever is the most conservative, is imposed in accordance with the O'Donnell and Langer design curve (Reference 28) for fatigue usage. This criterion is consistent with SRP Section 4.2 and has previously been approved in Reference 14. The NRC staff concludes that FCF's design criterion for cladding strain fatigue is applicable to M5 cladding up to currently approved burnup levels.

Evaluation - FCF has stated that the O'Donnell and Langer curve for irradiated Zircaloy (Reference 29), which includes a safety factor of 2 on stress amplitude or a factor of 20 on cycles (whichever is the more conservative), is conservative in relation to strain fatigue of M5 cladding. The staff asked FCF to supply their strain fatigue data for M5 cladding, and FCF supplied unirradiated M5 data in Reference 8. Examination of the M5 strain fatigue data demonstrates that the total strains from these tests are consistent with the unirradiated Zr-2 strain fatigue data of O'Donnell and Langer; therefore, M5 strain fatigue appears to be consistent with the O'Donnell and Langer curves for unirradiated Zr-2, 3, and 4. However, FCF uses the irradiated strain fatigue curve, with a safety factor of 2 on stress amplitude or a factor of 20 on cycles, from O'Donnell and Langer because it is more conservative than the unirradiated curve. The use of this curve and safety factor is conservative for determining M5 strain fatigue life. FCF introduces further conservatisms in this analysis by using the minimum, as-fabricated cladding thickness and subtracting metal loss based on the maximum calculated oxide layer thickness (Reference 2). The NRC staff concludes that FCF's analysis methodology for strain fatigue is conservative and, therefore, applicable to M5 cladding up to currently approved burnup levels.

3.4 Fretting Wear

Bases/Criteria - Fretting wear is a concern for fuel, burnable poison rods, and guide tubes. Fretting, or wear, may occur on the fuel and/or burnable rod cladding surfaces in contact with the spacer grids if there is a reduction in grid spacing loads in combination with small amplitude, flow induced, vibratory forces. Guide tube wear may result when there is flow induced motion between the control rod ends and the inner wall of the guide tube.

The FCF design criterion against fretting wear is that the fuel design shall provide sufficient support to limit fuel rod vibration and cladding fretting wear. This criterion is consistent with SRP Section 4.2 and has previously been approved in Reference 14. The NRC staff concludes that FCF's design criterion for cladding fretting wear is applicable to M5 cladding up to currently approved burnup levels.

Evaluation - Fretting wear resistance for the M5 alloy should be similar to standard Zr-4 material. In addition, the mechanisms for fretting wear such as grid spring relaxation loads and flow vibration are dependent on the spacer spring design and material, and spacer grid design flow characteristics rather than the cladding material.

As a result, FCF performs out-of-reactor vibration and wear tests (for more than 1000 hours) of a full assembly in a flow loop, and performs post-irradiation visual examination of LTAs to verify satisfactory fretting wear performance. This is performed by FCF when a significant change is made to the spacer springs, spacer grids or flow characteristics of an assembly design (Reference 14).

Therefore, a change in cladding material should not have a significant impact on fretting wear in current FCF fuel designs. The NRC staff concludes that the FCF test methodology for verifying fretting wear is applicable to M5 cladding up to currently approved burnup levels.

3.5 Oxidation and Crud Buildup

Bases/Criteria - Section 4.2 of the SRP identifies cladding oxidation and crud buildup as potential fuel system damage mechanisms. The SRP does not establish specific limits on cladding oxidation and crud but does specify that their effects be accounted for in the thermal and mechanical analyses performed for the fuel. Recent out-of-reactor measured elastic and plastic cladding strain values from high burnup cladding from two PWR fuel vendors (References 19, 20, and 21) have shown a decrease in Zr-4 cladding ductilities when oxide thicknesses begin to exceed 100μm. As a result, the NRC staff has encouraged fuel vendors to establish a maximum oxide thickness limit of 100μm. FCF has adopted this oxide thickness limit (Reference 2). The NRC staff finds this oxide limit acceptable for M5 cladding based on FCF's commitment to continue to collect oxide thickness and ductility data up to current burnup levels.

Evaluation - M5 corrosion is modeled by FCF using the same model with a different activation energy, COROSO2 (Reference 2), as used for their standard Zr-4 cladding. FCF has provided a large amount of M5 corrosion thickness data (maximum oxide measurement from over 370 rods and/or cycles where some rods have one measurement per cycle of operation) for burnups up to 53 GWd/MTU. The COROSO2 model (with M5 activation energy) comparisons to this data demonstrate that there is a reasonable agreement with the data with a small degree of predictive conservatism (higher oxide thickness) at high burnup levels. In response to a question on whether additional data had been obtained since the publication of the topical report, FCF responded (Reference 6) that they recently collected oxidation data from an M5 clad fuel rod that was reconstituted into a Zr-4 LTA that achieved a rod average burnup of 63 GWd/MTU. This M5 clad fuel rod achieved a maximum fuel rod corrosion thickness that was less than half the FCF limit on corrosion thickness.

Cladding oxidation is generally the most severe in plants with high coolant outlet temperatures and those with aggressive power histories (i.e., those plants that drive the fuel at high heat fluxes for long periods of time). Examination of the plants from which the FCF M5 corrosion data was collected has revealed that a significant amount of the data is from plants with high outlet temperatures. Some of the data is from fuel with a more aggressive operating history as well. However, the highest burnup data is from a plant with a lower outlet temperature and an operating history that was not particularly aggressive. FCF has committed to continue to collect data up to currently approved burnup levels from plants with higher outlet temperatures and more aggressive operating histories.

The NRC staff concludes that the FCF corrosion model for M5 cladding is acceptable for application to licensing analyses up to currently approved burnup levels, based on FCF's commitment to continue to collect M5 corrosion and ductility data up to approved burnup levels.

3.6 Rod Bowing

Bases/Criteria - Fuel and burnable poison rod bowing are phenomena that alter the design-pitch dimensions between adjacent rods. Bowing affects local nuclear power peaking and the local heat transfer to the coolant. Rather than place design limits on the amount of bowing that is permitted, the effects of bowing are included in the departure from nucleate boiling (DNB) analysis by a DNB ratio penalty when rod bow is greater than a predetermined amount. This methodology for rod bow is consistent with SRP Section 4.2 and has previously been approved in Reference 14. Thus the NRC staff concludes that FCF's rod bowing methodology is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - Rod bowing has been found to be dependent on rod axial growth, the distance between grid spacers, the rod moment of inertia, flux distribution and other assembly design characteristics. FCF has indicated in their submittal (Reference 1) that they will continue to use the approved rod bow methodology (used for their standard Zr-4 cladding) for the M5 cladding. FCF has not presented any rod bowing data for M5 cladding to indicate that the approved Zr-4 methodology will envelope M5 rod bow; however, they have stated they intend to collect rod bow data from LTAs with M5 cladding in calendar years 2000 and 2001 up to extended burnup levels. FCF has argued that M5 cladding should have less rod bowing than their standard Zr-4 cladding at a given burnup level because axial rod growth is less for M5 cladding. The NRC staff agrees that rod bow will most likely be less at a given burnup level but it is necessary to confirm this and to also confirm that rod bow with M5 cladding saturates at high burnup levels, similar to what has been observed in Zr-4 cladding.

The NRC staff concludes that the use of FCF's approved rod bow methodology for M5 cladding is acceptable for application to licensing analyses up to currently approved burnup levels, based on FCF's commitment to collect M5 rod bow data up to high burnup levels to confirm that the M5 rod bow is enveloped by the Zr-4 rod bow model.

3.7 Axial Growth

Bases/Criteria - The FCF design basis for axial growth is that adequate clearance be maintained between the rod ends and the top and bottom nozzles to accommodate the differences in the growth of fuel rods and the growth of the fuel assembly. Similarly, for assembly growth, FCF has a design basis that axial clearance between core plates and the bottom and top assembly nozzles should allow sufficient margin for fuel assembly irradiation growth during the assembly lifetime to prevent the holddown spring in the assembly upper end fitting from going solid at cold shutdown. These criteria are consistent with SRP Section 4.2 and have previously been approved in Reference 14. Thus the NRC staff concludes that the FCF design basis is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - FCF provides an initial fuel rod-to-nozzle growth gap in their fuel assembly designs to allow for differential irradiation growth and thermal expansion between the fuel rod cladding and the fuel assembly guide thimble tubes. If this gap were to close, an interference fit would develop that would result in fuel rod bowing. An interference fit can develop because the fuel rod cladding grows faster than the assembly guide tubes in the axial direction. FCF uses an upper tolerance limit (UTL) 95/95 (at least 95 percent probability, at a 95 percent confidence level) minimum gap model that bounds their shoulder gap data (the minimum measured gap closure per assembly is used), along with worst case fabrication tolerances and thermal expansion, to preclude interference during operation. This is a new methodology proposed by FCF for fuel assemblies with Zr-4 (cold-worked stress relief annealed) cladding and Zr-4 (fully annealed) guide tubes (Zr-4/Zr-4), with M5 cladding and Zr-4 (fully annealed) guide tubes (M5/Zr-4), and with M5 cladding and M5 guide tubes (M5/M5). Consequently, FCF has 3 UTL gap closure models for these three assembly combinations (i.e., Zr-4/Zr-4, M5/Zr-4, and M5/M5). The gap closure model for Zr-4/Zr-4 is based on a large data base with burnups up to 54 GWd/MTU, while the M5/Zr-4 closure model is based on measurements from approximately 19 individual assembly/cycles (minimum of approximately 56 gap measurements per assembly/cycle) with burnups up to 39 GWd/MTU. The M5/M5 model is only based on the minimum gap from 112 measurements from two assemblies after only one cycle of irradiation (approximately 22 GWd/MTU). Additional M5/M5 data will be obtained after two cycles of irradiation (approximately 45 GWd/MTU assembly burnup), scheduled in March of 2000, and three cycle data (approximately 55 GWd/MTU), scheduled in September 2001. FCF is also committed to obtaining gap closure data from M5/Zr-4 assembly up to currently approved burnup limits (see Section 6 on FUEL SURVEILLANCE). The NRC staff concludes that the FCF minimum gap closure models are acceptable for application to licensing analyses up to currently approved burnup levels, based on FCF's commitment to continue to collect Zr-4/M5 and M5/M5 gap closure data up to currently approved burnup levels.

In like manner FCF designs the holddown springs for the assembly to prevent the holddown spring from bottoming out on reactor-internals assuming maximum assembly growth and worst case tolerances. FCF utilizes upper bound 95/95 tolerance lines of their axial assembly growth data, along with worst case fabrication dimensions or 95/95 dimensional tolerances (when available), to assure that the holddown spring will not bottom out at end-of-life (EOL). As noted in Section 2.14 of this SE, FCF has presented UTL models for both Zr-4 and M5 assembly (guide tube/thimble) growth. FCF has over 80 assembly measurements of assembly growth with Zr-4 guide tubes for assembly burnups up to 58 GWd/MTU. Currently, FCF has only two data points for M5 guide tube growth at an assembly burnup of 22 GWd/MTU. The UTL curve for M5 assembly growth is very conservative compared to the two data points. FCF has committed to collecting further assembly growth data for M5 guide tubes in North Anna up to currently approved burnup levels (see Section 6, FUEL SURVEILLANCE). The NRC staff concludes that the Zr-4 and M5 UTL guide tube/thimble (assembly) growth models are acceptable for licensing applications up to currently approved burnup levels, based on FCF's commitment to continue to collect M5 assembly (guide tube) growth data up to approved burnup levels.

3.8 Rod Internal Pressure

Bases/Criteria - Rod internal pressure is a driving force for, rather than a direct mechanism of, fuel system damage that could contribute to the loss of dimensional stability and cladding integrity. To preclude fuel damage, SRP Section 4.2 presents a rod pressure limit of maintaining rod pressures below system pressure. The FCF design basis for the fuel rod internal pressure is that the fuel system will not be damaged due to excessive fuel rod internal pressure and FCF has established the "Fuel Rod Pressure Criterion" (Reference 23) to provide assurance that this design basis is met. The internal pressure of the FCF lead fuel rod in the reactor is limited to a value below that which could cause (1) the diametral gap to increase due to outward cladding creep during steady-state operation, and (2) extensive DNB propagation to occur. This FCF design basis and the associated limits have been approved by the NRC (Reference 23). The use of M5 cladding impacts the internal pressure limit because M5 cladding creep is different than that observed for their standard Zr-4. The M5 cladding creep model (with Zr-4 model upper bound uncertainties) is discussed in Section 2.10 of this SE and found to be acceptable for use in determining the rod pressure limits up to the currently approved burnup levels. The only difference in the rod pressure limit methodology for M5 cladding is the use of the new M5 creep model.

Evaluation - FCF utilizes the TACO-3 fuel performance code (Reference 22) for predicting EOL fuel rod pressures to verify that they do not exceed the FCF "Fuel Rod Pressure Criterion" during normal operation and AOOs. The FCF rod pressure analysis methodology has not changed other than the use of M5 properties in TACO-3. The use of M5 cladding will not significantly change the TACO-3 prediction of rod pressures; however, the change in the following material properties will have a small impact on the rod pressure analyses: thermal expansion, thermal conductivity, creep, poison's ratio, modulus of elasticity, and axial growth. These properties have all been reviewed and found acceptable in Sections 2.2, 2.3, 2.10, 2.11, 2.12, and 2.14, respectively.

The NRC staff concludes that the FCF analysis methodology, using TACO-3 and M5 properties, for determining rod internal pressures for rods with M5 cladding is acceptable up to currently approved burnup levels.

4.0 FUEL ROD FAILURE

In the following paragraphs, fuel rod failure thresholds and analysis methods for the failure mechanisms listed in the SRP will be reviewed. When the failure thresholds are applied for normal operation, including AOOs, they are used as limits (and hence SAFDLs) since fuel failure under those conditions should not occur according to the traditional conservative interpretation of GDC 10. When these thresholds are used for postulated accidents, fuel failures are permitted, but they must be accounted for in the dose assessments required by 10 CFR Part 100. The basis for establishing these failure thresholds is thus established by GDC 10 and Part 100, and only the threshold values and the analysis methods used to assure the thresholds are met will be reviewed below.

4.1 Hydriding

Bases/Criteria - Internal hydriding as a cladding failure mechanism is precluded by controlling the level of hydrogen impurities in the fuel during fabrication; this is generally an early-in-life failure mechanism. Internal hydriding is not impacted by the use of M5 cladding and, therefore, will not be discussed further in this SE.

External hydriding of M5 cladding due to waterside corrosion is the other source and is limited by FCF's 100μm limit on oxide thickness, as discussed in Section 3.5 of this SE.

Evaluation - FCF controls internal hydriding by taking statistical samples following pellet fabrication, prior to loading the pellets in the fuel rods, and confirming that hydrogen is below a specified level. Therefore, no analyses are necessary other than to confirm that the statistical pellet sampling shows that hydrogen is below the specified level. The use of M5 cladding does not impact the internal hydriding. The staff considers this acceptable.

4.2 Cladding Collapse

Bases/Criteria - If axial gaps in the fuel pellet column were to occur due to fuel densification, the potential would exist for the cladding to collapse into a gap (i.e., flattening). Because of the large local strains that would result from collapse, the cladding is then assumed to fail. It is an FCF design criterion that cladding collapse is precluded during the fuel rod design lifetime. This design basis is the same as that in the SRP and has been previously approved (Reference 14). This design criteria is not affected by the use of M5 cladding. The NRC staff concludes that this FCF design criterion is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - The FCF analytical models for evaluating cladding creep collapse are the approved CROV and TACO-3 computer codes (References 30 and 22). The application of these codes to calculating creep collapse is discussed in Reference 30. The TACO-3 code will include the M5 material property models discussed in Section 2.0 of this SE. As discussed in Section 2.10

of this SE, the new M5 creep model (Reference 7) is more conservative for calculating creep collapse in CROV than the old Zr-4 creep model originally used in CROV. Therefore, FCF has adopted the more conservative M5 creep model, along with the Zr-4 model uncertainties, for use in determining the upper bound creep for use in CROV for cladding collapse analyses. The NRC staff concludes that the use of the TACO-3 and CROV codes with the appropriate M5 material property models is acceptable for creep collapse analyses for fuel rods with M5 cladding up to currently approved burnup levels.

4.3 Overheating of Cladding

Bases/Criteria - The FCF design criterion for the prevention of fuel failures due to overheating is that there will be at least 95 percent probability, at a 95 percent confidence level, (95/95) that DNB will not occur on a fuel rod during normal operation and AOOs. This design limit is consistent with the thermal margin criterion of the SRP guidelines and has previously been approved. This design criterion is not affected by the use of M5 cladding. The NRC staff concludes that this FCF design criterion is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - As stated in SRP Section 4.2, adequate cooling is assumed to exist when the thermal margin criterion to limit DNB, or boiling transition, in the core is satisfied. The impact of the use of M5 cladding on DNB is small and related to the small change in gap conductance (due to differences in gap size from M5 creep down and thermal expansion) and M5 thermal conductivity. Other than the small changes in M5 material properties the FCF methodology for evaluating DNB has not changed. These M5 properties have been reviewed by the NRC staff in Section 2.0 of this SE and found to be acceptable for use in FCF licensing analyses up to currently approved burnup levels.

4.4 Overheating of Fuel Pellets

Bases/Criteria - To preclude overheating of fuel pellets, FCF design criterion is that no fuel centerline melting is allowed for normal operation and AOOs. This design criterion is the same as given in SRP Section 4.2 and has previously been approved (Reference 14). This design criterion is not affected by the use of M5 cladding. The NRC staff concludes that this FCF design criterion is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - FCF utilizes the approved TACO-3 (Reference 22) fuel performance code to determine the maximum linear heat generation rate (LHGR) at which a given fuel design will not achieve fuel melting at a 95 percent probability at a 95 percent confidence level. This FCF analysis methodology has previously been found to be acceptable up to a rod-average burnup of 62 GWd/MTU (Reference 30). FCF was asked to provide an example fuel melting analysis with M5 cladding properties. In Reference 5, FCF provided example fuel melting analyses for both M5 and Zr-4 cladding that demonstrated nearly identical results. Therefore, the small changes in M5 cladding properties has an insignificant impact on fuel melting analyses. The NRC staff concludes that the use of the TACO-3 code with the appropriate M5 material property models is acceptable for fuel melting analyses for fuel rods with M5 cladding up to currently approved burnup levels.

4.5 Pellet-Cladding Interaction (PCI)

Bases/Criteria As indicated in SRP Section 4.2, there are no generally applicable criteria for PCI failure. However, two acceptable criteria of limited application are presented in the SRP for PCI: (1) less than 1 percent transient-induced cladding strain, and (2) no centerline fuel melting. Both of these limits are used by FCF as discussed in Sections 3.2 and 4.4 of this SE and, therefore, have been addressed by FCF.

Evaluation - As noted earlier, FCF utilizes the TACO-3 (Reference 22) code to show that their fuel meets both the cladding strain and fuel melting criteria. The NRC staff concludes that this code is acceptable per the recommendations in Sections 3.2 and 4.4 of this SE.

4.6 Cladding Rupture

Bases/Criteria - There are no specific design limits associated with cladding rupture other than the 10 CFR Part 50, Appendix K (Reference 31) requirement that the incidence of rupture not be underestimated. A cladding rupture temperature correlation must be used in the LOCA emergency core cooling system (ECCS) analysis. The cladding rupture temperature for M5 cladding is similar to Zr-4; however, FCF has elected to collect M5 cladding rupture temperature data versus hoop stress at various heating rates similar to what was done for Zr-4 in NUREG-0630 (Reference 32). The M5 rupture temperature model will be discussed in the Evaluation section below.

Evaluation - FCF has collected a large amount of M5 cladding rupture temperature data at slow and fast heating rates. The slow heating rate data (between 2 to 15°C/sec) determined rupture temperatures at stresses between 1 to 13.5 Ksi (kilo-pounds per square inch). The fast heating rate (25 to 100°C/sec) determined rupture temperatures at stresses between 1 to 10.5 Ksi. FCF has developed a new correlation for rupture temperature as a function of cladding hoop stress and heating rate in Reference 8 that is slightly different from the original submittal. The resulting rupture curves from this correlation are very similar to the NUREG-0630 curves with the exception that they have a steeper decrease in rupture temperature with stress at stresses below 5 Ksi (which was a characteristic of the M5 data). In addition, these rupture curves appear to span the breadth of the M5 data very similar to how the NUREG-0630 curves spanned the breadth of the Zr-4 rupture data. PNNL and the NRC staff have examained the M5 rupture correlation and data and agree that the correlation (1) is a reasonable relationship with the data, (2) is similar to the NUREG-0630 curves, and (3) meets the intent of Appendix K of 10 CFR 50.46 that the degree of swelling and incidence of rupture not be underestimated. The NRC staff concludes that the FCF rupture correlation for M5 cladding is accetable for determining rupture temperatures for LOCA ECCS analyses up to currently approved burnup levels.

4.7 Fuel Rod Mechanical Fracturing

Bases/Criteria - The term "mechanical fracture" refers to a fuel rod defect that is caused by an externally applied force such as a hydraulic load or a load derived from core-plate motion. The design limit proposed by FCF to prevent fracturing is that the stresses due to postulated accidents in combination with the normal steady-state fuel rod stresses should not exceed the yield strength of the components in their fuel assemblies. This design criterion for fuel rod mechanical fracturing is consistent with the SRP guidelines, and has previously been approved (Reference 14). While the yield strength has changed for M5 cladding, as discussed in Section 2.8 of this SE, the FCF design criterion has not changed. Therefore, the design criterion is not affected by the use of M5 cladding. The NRC staff concludes that this FCF design criterion is acceptable for licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - The mechanical fracturing analysis is done as a part of the seismic-and-LOCA loading analysis. A discussion of the seismic-and-LOCA loading analysis is given in Section 5.4 of this SE.

5.0 FUEL COOLABILITY

For postulated accidents in which severe fuel damage might occur, core coolability must be maintained as required by several GDCs (e.g., GDC 27 and 35). In the following paragraphs, limits and methods to assure that coolability is maintained are discussed for the severe damage mechanisms listed in the SRP.

5.1 Fragmentation of Embrittled Cladding

Bases/Criteria - The most severe occurrence of cladding oxidation and possible fragmentation during a postulated accident is the result of a LOCA. In order to reduce the effects of cladding oxidation during a LOCA, FCF uses a limiting criterion of 2200°F on peak cladding temperature (PCT) and a limit of 17 percent on maximum cladding oxidation as prescribed by 10 CFR 50.46. These criteria are consistent with SRP criteria and have previously been approved (Reference 14). FCF has performed high-temperature oxidation and quenching tests with M5 cladding to demonstrate that the 2200°F (1204°C) PCT and 17 percent oxidation limits protected the cladding against embrittlement and prevent the oxidation from becoming autocatalytic. This was demonstrated by FCF by heating M5 (Zr-4 was also tested) cladding to high temperatures of 1100, 1200, and 1300°C for various times and quickly (less than one second) quenching the cladding in a cold water bath (discussed in Appendix G of Reference 1). The cladding was removed from the bath and tested under pressure for leaks and oxide thickness measured. These tests demonstrated that failure did not occur until 20 to 25 percent of the cladding was oxidized, which is nearly identical to the test results for Zr-4 cladding in this test and other similar tests available to NRC, and no autocatalytic oxidation was observed. These FCF tests confirm that the 2200°F PCT and 17 percent oxidation criteria are conservative for M5 cladding in order to prevent cladding embrittlement and fragmentation during a LOCA. The NRC staff concludes that this FCF design criterion is acceptable for LOCA licensing analyses with M5 cladding up to currently approved burnup levels.

Evaluation - FCF uses approved LOCA evaluation models along with the Baker-Just correlation, as required by 10 CFR Part 50 Appendix K, for demonstrating compliance with the 2200 °F PCT and 17 percent oxidation criteria for the fuel cladding during a LOCA. FCF has performed high-temperature oxidation tests for M5 cladding (Appendix D of Reference 1) to confirm that the Baker-Just oxidation correlation remains conservative in relation to M5 high-temperature oxidation. The FCF high temperature oxidation tests were performed in super heated flowing steam where the sample (both M5 and Zr-4) was inductively heated to temperatures of 1050, 1150, and 1250°C for various times. The measured oxidation rates for the M5 samples were significantly lower than those for the Zr-4 samples at 1050°C; however, at 1150 and 1250°C the oxidation rates were nearly identical. A comparison of M5 measured values to Baker-Just predictions demonstrated that the Baker-Just correlation remained conservative for temperatures typically calculated for LOCA. The staff asked FCF (Reference 4) to provide Arrehenius plots of the high-temperature oxidation data in order to provide a measure of bias and uncertainty in the data. FCF provided these plots (Reference 6) which demonstrated only small uncertainties and essentially no biases in the data. The FCF data demonstrates that high-temperature oxidation of the M5 alloy is bounded by the Baker-Just correlation and that the Appendix K requirement for the use of Baker-Just remains conservative in relation to the use of M5.

FCF provided example LOCA analyses (Appendix F of Reference 1) with M5 and Zr-4 cladding at beginning-of-life (BOL) and at a burnup of 40 GWd/MTU to demonstrate that the results were only slightly different between M5 and Zr-4.

The staff noted that the peak oxidation values calculated by FCF (Table F-3) for 40 GWd/MTU did not appear to include the initial oxidation that resulted from normal steady-state operation. It is noted that NRC Information Notice (IN) 98-29, dated August 28,1998, stated that initial oxidation thickness should be included in the peak oxidation calculated for LOCA to demonstrate compliance with 10 CFR 50.46 (17 percent oxidation criterion). In response to the staff's questions, FCF stated that while initial oxidation was included in the LOCA analysis at 40 GWd/MTU, the value was significantly lower than what would be the measured oxidation at a burnup of 40 GWd/MTU. FCF noted that the generic issue of whether to include initial oxidation in the 17 percent criterion is being disputed by NEI and fuel vendors. FCF further noted that they have committed to NRC to check their LOCA analyses to provide assurance that the 17 percent oxidation criterion will not be exceeded if such an approach were required by the NRC. The staff concludes that this generic issue is independent of the review of the subject topical report and will not be considered in this SE.

The NRC staff concludes that the Baker-Just correlation is conservative for determining high temperature M5 oxidation for LOCA analyses and, therefore is acceptable for LOCA ECCS analyses up to currently approved burnup levels.

5.2 Violent Expulsion of Fuel

Bases/Criteria - In a severe reactivity insertion accident (RIA), such as a control rod ejection accident, large and rapid deposition of energy in the fuel could result in melting, fragmentation, and dispersal of fuel. The mechanical action associated with fuel dispersal might be sufficient to destroy the fuel cladding and rod bundle geometry and to provide significant pressure pulses in the primary system. To limit the effects of an RIA event, Regulatory Guide 1.77 (Reference 33) recommends that the radially-averaged energy deposition at the hottest axial location be restricted to less than 280 cal/g. In addition, the fuel failure limit is the onset of DNB for determining the dose consequences of an RIA. The limiting RIA event for FCF fuel designs is a control rod ejection accident.

FCF's safety criteria for the control rod ejection accident is that the radial average peak fuel enthalpy for the hottest fuel rod shall not exceed 280 cal/g. This is identical to the guidance in SRP Section 4.2 and Regulatory Guide 1.77 (References 10 and 33). It is noted that the NRC staff is currently reviewing the 280 cal/gm limit and the limit for fuel failure may be decreased for fuel at high burnups. Recent RIA testing has indicated the fuel expulsion and fuel failure may occur before the 280 cal/gm limit and the onset of DNB, respectively (References 34 and 35). However, further testing and evaluation is needed to better establish new limits. The fuel expulsion and failure limits for an RIA may decrease in the future, but the current limits continue to be accepted by the staff and the use of M5 cladding is not expected to significantly impact these safety criteria. The NRC staff concludes that the FCF RIA criteria are valid for licensing applications up to currently approved burnup levels.

Evaluation - FCF verifies that this acceptance criterion is met for each fuel cycle through design and cycle specific analyses, and by limiting the ejected rod worth. The industry and NRC have both done preliminary evaluations of the worst impact of both a lower enthalpy limit for fuel expulsion and lower failure limit at current burnup limits. These very conservative analyses indicate that maximum enthalpies for high burnup rods are at least a factor of three lower than the current 280 cal/gm limit and violent expulsion is unlikely. In addition, the dose consequences are within those specified in 10 CFR Part 100. The use of M5 cladding has little impact on fuel expulsion and failure (compared to the use of Zr-4) as long as the cladding remains ductile under the operating conditions of this event (see Section 2.9 of this SE on Ductility). The impact of the use of M5 cladding on DNB is small due to the small changes in M5 material properties (as noted in Section 4.3 of this SE) and the FCF approved methodology for evaluating RIAs has not changed. The M5 properties have been reviewed by the NRC staff (see Section 2 of this SE) and found to be acceptable for use in FCF licensing analyses up to currently approved burnup levels.

5.3 Clad Ballooning

Bases/Criteria - Zircaloy cladding will balloon (swell) under certain combinations of temperature, heating rate, and stress during a LOCA. There are no specific design limits associated with cladding ballooning other than the 10 CFR Part 50 Appendix K requirement that the degree of swelling not be underestimated. To meet the requirement of 10 CFR Part 50 Appendix K, the burst strain and the flow blockage resulting from cladding ballooning must be taken into account in the overall LOCA analysis. Cladding ballooning is a result of high-temperature creep and deformation of the cladding. The M5 alloy has different high-temperature creep and deformation characteristics than Zr-4. As a result, FCF has developed new ballooning and flow blockage models for M5 cladding similar to the methodology developed in NUREG-0630 for Zr-4 and Zr-2 cladding (recommended in SRP Section 4.2). These FCF ballooning and flow blockage models for M5 will be discussed in the Evaluation section below.

Evaluation - The M5 cladding has different high-temperature creep characteristics and different $\alpha \rightarrow \beta$ transformation temperatures than Zr-4 cladding and, therefore, the cladding burst strain and flow blockage models developed in NUREG-0630 (Reference 32) for Zr-4 cladding are not applicable to M5 cladding. Therefore, FCF performed single-rod (with M5 cladding) ballooning tests in the EDGAR test facility and measured cladding strains as a function of temperature for fast and slow heating rates, similar to what was done in NUREG-0630 for Zr-4. FCF also performed single-rod ballooning tests and measured cladding burst strains for Zr-4 cladding using the same EDGAR facility, equipment and methodology as used for M5 cladding. The staff has compared the FCF Zr-4 burst strain results to the results in NUREG-0630 and found that the FCF measured strains were greater for both fast and slow heating rates and at all temperatures in the α and β regions. This would indicate that either the FCF Zr-4 cladding has higher creep rates than the Zr-4 cladding used in the NUREG-0630 tests or that the EDGAR test facility results in conservatively higher measured strains than the facility used in NUREG-0630 burst tests. Also a comparison of the M5 and Zr-4 measured burst strains from the EDGAR facility demonstrates that the M5 cladding has lower burst strains and, therefore, less strain capability than Zr-4. The NRC staff concludes that the single-rod strain data collected in the EDGAR facility are in general more conservative than the single-rod data used in NUREG-0630 and, therefore, are acceptable for use in developing M5 cladding ballooning and flow blockage models.

Single rod burst strains need to be translated to flow blockage in an actual fuel assembly (bundle). The flow blockage model in NUREG-0630 relied on three bundle tests (performed by Oak Ridge) under simulated LOCA heating (two bundles at fast and one bundle at slow heating rates) to relate the single rod burst strain data to the measured bundle flow blockages. FCF has not performed their own bundle tests with M5 cladding but instead has relied on the three Oak Ridge bundle tests from Appendix A of NUREG-0630 to model the relationship between single-rod burst and pre-rupture strains, and assembly flow blockages.

There are differences between the FCF methodology for calculating M5 cladding flow blockage and the flow blockage model developed in NUREG-0630 from single-rod burst strains. FCF has measured the burst strains at the rupture location, as discussed above, the same as in NUREG-0630, but in addition they have also measured the strain remote from the rupture location (20 mm on both sides of the rupture location) from their single-rod EDGAR tests. They assume that the axial strains decrease exponentially away from the ± 20 mm rupture location, and this exponential function is derived from the axial measured strains of the individual rods in the Oak Ridge bundle tests from NUREG-0630. FCF has further assumed that, in addition to the burst strains, the remote strain (referred to by FCF as pre-rupture strain or just pre-strain) also makes a major contribution to assembly flow blockage. NUREG-0630 also recognized that axial strains remote from the failure location, and also strains in non-failed rods, significantly contributed to the flow blockage in a bundle (assembly). NUREG-0630 assumed that the pre-rupture strains were proportional to the burst strains, and used a proportionality constant to relate the single-rod burst strains to bundle flow blockage (which was based on the flow blockages measured in the bundle tests). FCF was asked why a similar assumption was not also made for M5 cladding. FCF responded that M5 pre-rupture strains were not always the same proportionality to burst strains within all temperature ranges and, therefore, this assumption was not valid for M5 cladding.

The following discussions will be divided up into subsections in order to evaluate each component of the FCF methodology for calculating assembly flow blockage with M5 cladding. The first subsection will discuss the general characteristics of high-temperature strain data for zirconium alloys for background information for interpreting the Zr-4 and M5 data. The second subsection will discuss the adequacy of the FCF single rod burst strain curves (for fast and slow heating rates) used for calculating the extent of M5 assembly flow blockage. The third subsection will discuss the adequacy of the FCF pre-rupture strain curves (for fast and slow heating rates) also used for calculating the extent of M5 assembly flow blockage. The fourth subsection will address the adequacy of the overall FCF methodology for calculating assembly flow blockage with M5 cladding.

5.3.1 General Characteristics of High Temperature Zirconium Alloy Strains

It is important to understand the general characteristics of the trends of burst and pre-rupture strain data as a function of high temperature in zirconium alloys. This is because the zirconium α-β phase transformation temperatures have a significant impact on the shape of the burst strain data and, therefore, in the development of strain curves. The Zr-4 burst strain data and correlation in NUREG-0630 for both slow and fast heating rates has two strain peaks; one near the start of the α-β phase transformation temperature, and the second peak near the completion of the β phase transformation temperature. Burst strains significantly decrease in the α+β phase region because ductility in this phase is significantly lower than in the pure α phase or the pure β phase. The burst strains in the pure β phase start to decrease at higher temperatures (above where the peak strain is observed) because of embrittlement due to oxidation. For the fast heating rate data there is generally a shift in the burst strain peaks to slightly higher temperatures than for the slow ramp data because the kinetics of the phase transformation are not fast enough to keep up with the fast heating rates. This information is important in understanding the results of the M5 burst strain data and in developing correlations from the data because there is a significant amount of scatter in this data (Zr-4 burst strain data also has considerable scatter) and several different curves could be drawn to represent this data without this background information.

5.3.2 Burst Strain (Slow and Fast Heating Rate) Curves

The FCF slow heating rate data base for M5 is fairly large in the α and α+β phase regions where it is principally applied in FCF LOCA analyses; however, there were only four data points in the pure β phase region. The original FCF burst strain curve for M5 cladding (Reference 1) either bounded or agreed with nearly all of the burst strain data for slow heating rates. The burst strain peak in the α phase was very near the temperature where the α-β phase transformation starts but the second peak was at a considerably higher temperature (about 100 °C higher) than the temperature at which the β phase transformation is complete. This delta temperature difference is greater than what would be expected for slow heating rates. Consequently, FCF agreed (Reference 8) to shift the second burst strain peak to a lower temperature to better match the temperature at which the β phase transformation is complete. The shift in the temperature for this peak did not impact the agreement with the data in the β phase region. The NRC staff has reviewed the burst strain data and FCF slow heating rate curve for M5 cladding (Reference 8) and conclude that the FCF curves bound the majority of the burst strain data and, therefore, are conservative and acceptable.

The quantity and temperature range of the M5 fast heating rate data was considerably less than collected for the slow heating rate data. Nearly all of the fast heating rate data was located in a narrow temperature range (100 °C), where the α+β phase transformation takes place and displays low ductility (strains), although there were a couple of data taken in the higher temperature β phase region. The staff asked FCF about the lack of fast heating rate burst data outside of the 100 °C range. FCF responded that this is the temperature range where the fast heating rates are calculated to occur for M5 fuel (using the M5 fast heating rate rupture temperature curves for LOCA analyses, as discussed in Section 4.6 of this SE). The location of the burst strain peaks in the α and β regions of the FCF fast heating rate curve, in relation to the α→β phase transformation temperatures, is consistent with what is observed for the Zr-4 burst strain curve found in NUREG-0630. The FCF fast heating rate curve either bounds or agrees well with the majority of fast heating rate data. The NRC staff has reviewed the FCF slow and fast heating rate burst strain curves for M5 cladding and concludes that the FCF curves bound the majority of the burst strain data and, therefore, are acceptable.

FCF has also developed a probability distribution function (PDF) for the axial position of cladding rupture. This PDF is based on the cladding temperature distribution between grids with the distribution being zero near the grid locations. Given a relatively even (constant) temperature distribution in the cladding, as conservatively assumed for LOCA burst strains, the location of the burst failure appears to be random based on the NUREG-0630 bundle tests. This PDF developed by FCF is a reasonably conservative estimate of the probability distribution of rupture locations within an assembly. The NRC staff has also reviewed the PDF used by FCF to determine the axial locations of rupture and concludes that they are reasonable and, therefore, acceptable.

5.3.3 Pre-Rupture Strain (Slow and Fast Heating Rate) Curves

The EDGAR test pre-rupture strain data and resulting FCF curves developed for the M5 cladding for both slow and fast heating rates have been examined. The pre-rupture strains were measured from the FCF single-rod burst tests. The corresponding temperature ranges for the pre-rupture strains are therefore, the same as for the burst strain data. Both the slow and fast heating rate curves, developed by FCF for predicting pre-rupture strains, assumed constant strains in the α and α+β phase regions, while examination of the slow heating rate data shows that higher strains were measured on average in the α phase than in the α+β phase. This is consistent with the higher strains observed in the α phase with the M5 burst strain data, the NUREG-0630 Zr-4 burst strain data, and the FCF Zr-4 pre-rupture strain data, compared to the lower strains observed in the α+β phase. In addition, the location of the β phase peak for both the slow and fast heating rate curves were at higher temperatures than observed for the peaks in the burst strain data, and at significantly higher temperatures than observed for the β phase transformation temperature. The staff asked FCF why these characteristics of the FCF pre-strain rupture curves did not match their own pre-rupture strain and burst data, and also did not match the strain behavior observed in other zirconium alloys.

FCF responded (Reference 8) with new pre-rupture strain (for slow and fast heating rates) curves with strain peaks in the α phase that provided much better agreement with the pre-rupture strain data. These new curves also shifted the peak strains for the β phase to better coincide with the peaks observed in the burst strain data and better agree with the β phase transformation temperature. The NRC staff has reviewed the M5 pre-rupture strain curves in Reference 8 and concludes that they are reasonable representations of M5 cladding strains at high cladding temperatures typical of LOCA and, therefore, are acceptable.

5.3.4 Overall Evaluation of Flow Blockage Methodology

For the LOCA analysis, FCF calculates burst and pre-rupture strains for all fuel rods in an assembly based on their cladding stresses and temperatures. Using these burst and pre-rupture strains, FCF calculates the geometry for all rods and resulting flow blockage in the assembly. While the individual models that make up the clad ballooning and flow blockage methodology have been reviewed in the above subsections and found to be conservative, this does not ensure that FCF's methodology for applying these models yields conservative and acceptable results. The only reference point for an acceptable flow blockage methodology is the methodology provided in NUREG-0630.

Consequently, the staff asked FCF to perform a direct comparison between the FCF methodology for determining flow blockage, the NUREG-0630 blockage curves for slow and fast heating rates, and the three Oak Ridge bundle blockage data provided in Appendix A of NUREG-0630.

FCF provided a comparison of their predicted blockage (local and assembly average blockage) results using their Zr-4 burst and pre-rupture strain curves, based on their EDGAR Zr-4 test results and their blockage methodology (Reference 8), to those predicted using NUREG-0630 curves and methodology. The FCF (Zr-4) predicted local flow blockage results for both slow and fast heating rates (Figures I-G.9 and I-G.10, respectively in Reference 8) demonstrated that the FCF methodology predicted greater assembly flow blockages at nearly all temperature ranges than was predicted by NUREG-0630 (blockage curves from Figures 14 and 15 in NUREG-0630). (The staff notes that the peak local blockage in the α phase predicted by the FCF methodology at the slow heating rates was only slightly greater than the local blockage predicted by NUREG-0630 in this temperature range.) In addition, FCF included comparisons to actual local flow blockage data from the three Oak Ridge bundle tests (References 36, 37 and 38) and from other bundle tests (Reference 32) to demonstrate that the FCF blockage methodology bounded all of this data. FCF has also provided assembly average flow blockage results for fast and slow heating rates (Figures I-G.7 and I-G.9, respectively, in Reference 8) to demonstrate similar conservatism between the FCF and NUREG-0630 blockage methodology for the local predicted FCF blockages. The NRC staff concludes that the FCF methodology for predicting clad ballooning (strains) and flow blockage are either as conservative or more conservative than the flow blockage model in NUREG-0630 (which is recommended for use by Section 4.2 of the SRP).

FCF has also argued that both the single-rod burst and bundle tests are conservative because they do not take into account the cladding hot spots as a result of asymmetric pellets and unheated surfaces in a commercial fuel assembly. These phenomena result in azimuthal temperature variations in the cladding that will limit cladding strains while the single rod and bundle tests have tried to eliminate any temperature variations to get the highest strains possible. The NRC staff agrees that there may be some conservatism built into the test data, but the temperature gradients in an actual assembly should not be large because part of the LOCA is nearly an adiabatic heatup which will tend to decrease temperature gradients.

The NRC staff concludes that the FCF methodology for determining M5 cladding ballooning and flow blockage is conservative for LOCA analyses and, therefore is acceptable for LOCA ECCS analyses up to currently approved burnup levels.

5.4 Fuel Assembly Structural Damage From External Forces

Bases/Criteria - Earthquakes and postulated pipe breaks in the reactor coolant system would result in external forces on the fuel assembly. Appendix A to SRP Section 4.2 states that the fuel system coolable geometry shall be maintained and damage should not be so severe as to prevent control rod insertion during seismic and LOCA events. FCF has adopted the SRP guidelines as their design bases and the use of M5 cladding does not alter these design bases.

Evaluation - FCF uses NRC-approved methodologies provided in Reference 14 for evaluating seismic and LOCA loads. The FCF methodology has not changed but part of the methodology requires using the yield and/or ultimate tensile strengths for the guide tubes/thimbles, as per ASME Section III of the Boiler Pressure Vessel Code (Reference 18). Should M5 alloy be used for the guide tubes/thimbles the M5 yield and ultimate tensile strengths will be used for this analysis. As noted in Sections 2.7 and 2.8 of this SE, the FCF relationships for yield and ultimate tensile strength for the M5 alloy are acceptable for licensing analyses. Therefore, the NRC staff concludes that the FCF methodology for seismic-and-LOCA loads using M5 yield and ultimate tensile strengths is acceptable up to currently approved burnup levels.

6.0 FUEL SURVEILLANCE

The staff asked FCF about what future fuel surveillance would be performed to verify satisfactory performance of the M5 alloy because very little data exists up to currently approved rod-average burnup levels of 62 GWd/MTU and 60 GWd/MTU for Mark-B and Mark-BW designs, respectively. FCF responded (Reference 8) that their LTA program consists of performing pool-side examinations of cladding oxide thickness, assembly length and bow, rod diameter (M5 creep data), rod length (growth measurement), guide tube oxide thickness, and rod extraction measurements along with visual examinations from 10 LTAs. It is noted that many of these LTAs represent only a partial loading of fuel rods with M5 cladding. In addition, FCF noted that they intend to perform hot cell examinations of individual M5 fuel rods to continue measuring mechanical properties, cladding hydrogen content, rod length, profileometry (cladding diameter), and oxide thicknesses. FCF was further asked about obtaining rod bow measurements because they currently do not have any rod bow data (see Section 3.6 of this SE). FCF responded (Reference 9) that they plan to perform rod bow measurements on the North Anna LTAs. FCF also stated that the pool-side measurements will include rod-shoulder to upper-tie-plate gap closure and M5 assembly growth (guide tube). Further, FCF stated that the hot cell laboratories will be asked to measure uniform and total strains of high burnup M5 cladding, along with micrographs of the failure surfaces in order to assess M5 ductility. FCF also committed (Reference 9) to obtain cladding strain, oxidation, hydride, rod bow, and axial growth (including shoulder gap closure) data up to the current approved rod-average burnup levels of 62 GWd/MTU and 60 GWd/MTU for Mark-B and Mark-BW designs, respectively.

The NRC staff concludes that the FCF fuel surveillance program for M5 alloy will address the current lack of data up to approved rod-average burnup levels of 62 GWd/MTU and 60 GWd/MTU for Mark-B and Mark-BW designs, respectively. Therefore, the NRC concludes that the FCF fuel surveillance program for M5 is acceptable.

7.0 LOCA EVALUATIONS WITH M5

BAW-10227-P, Appendix F, "M5 LOCA Evaluations," describes modifications in the use of Framatome approved large break loss-of-coolant accident (LBLOCA) and small break loss-of-coolant accident (SBLOCA) ECCS evaluation models to account for the presence of M5 fuel. Appendix F discusses the analysis methods, changes to the analysis methods to accommodate the presence of M5 fuel, sensitivity studies to show model convergence and conservatism, calculated results, and compliance with 10 CFR 50.46.

As discussed in other sections of this SE, the material properties of M5 are similar to those of other zirconium-based materials which have been previously licensed for use as cladding material. Based on this similarity, the staff finds it appropriately conservative to apply the criteria of 10 CFR 50.46 and 10 CFR Part 50, Appendix K when reviewing M5 fuel applications, including Appendix F of BAW-10227P. In performing this review, the staff has granted no exceptions in the application of these criteria. Although M5 is similar to Zircaloy, the criteria in the evaluation are specifically identified as appropriate for Zircaloy-clad fuel. Thus, exemptions must be obtained to allow application of those criteria to M5-clad fuel. Similarly, exemptions must be obtained to allow application of 10 CFR 50.44 dealing with hydrogen generation and combustible gas control to plants with M5-clad fuel.

BAW-10227-P, Appendix F, identifies changes in the use of the FCF LBLOCA and SBLOCA evaluation models to account for M5 material properties, including cladding conductivity, cladding creep, clad swelling, rupture deformation, and temperature. The material properties of M5 were found to be very similar to those of Zircaloy-4.

The Framatome models retain the methodology given in 10 CFR Part 50 Appendix K for the treatment of material properties, when prescribed by Appendix K and justified as suitably conservative. The retention of the Baker-Just equation for the calculation of metal/water reaction rate specified in Appendix K is such a case.

The swelling and rupture model for M5 cladding follows the approach of NUREG-0630 and meets the intent of NUREG-0630, as discussed in Section 4.6 of this SE. Section C.4 of BAW-10227P discusses post-LOCA droplet interaction modeling. Section C.4 indicates that the modeling of droplet interactions involves the thermodynamics of the fluid and the characteristics of the fuel, including its geometry. Sections 4.6 and 5.3 of this SE discuss M5 cladding deformation, including post-LOCA ballooning and rupture. These SE sections conclude that the fuel models in the FTI LOCA methodologies acceptably simulate M5 fuel performance, consistent with regulatory guidance.

The fluid thermodynamics models of the FTI LOCA methodologies are unchanged from those in the approved FTI LOCA analysis methodologies. The specific models which address droplet interaction, including consideration of post-LOCA cladding deformation, are presented in the FTI Topical Report BAW-10166P Rev.2, "BEACH- Best Estimate Analysis Core Heat Transfer - A Computer Program for Reflood Heat Transfer," which was approved by letter dated August 13, 1990 (Reference 39), for analyses with Zircaloy cladding, with certain usage restrictions. From its review, the staff concluded that the FTI LOCA models, with the same usage restrictions except as addressed in this SE, that were approved for analyses assuming Zircaloy-clad fuel are acceptable for LOCA analyses assuming M5-clad fuel. This conclusion is based on the previous approvals of the LOCA models, the acceptability of the M5 fuel material characteristics modeling, the similarity of M5 and Zircaloy material properties, and the limited sensitivity of the analysis results to the difference in materials.

Although fuel pin cladding within a fuel assembly can swell prior to rupture creating a bulge that interferes with the local coolant passage, FTI LOCA evaluation models do not include flow diversion around this swelling until after a rupture has been calculated. This was found not to be non-conservative for cladding swell up to 20 percent, as is documented in the SE for the "BEACH" code (BAW-10166) dated August 13, 1990 (Reference 39). This SE concluded, "For any licensing analyses where cladding swell exceeds 20 percent, but does not rupture, the user should justify the acceptability." Calculated M5 fuel cladding swell can exceed 20 percent prior to rupture in LOCA analyses. In a letter dated January 14, 2000, FTI presented information from two reports, P. Ihle and K. Rust, "FEBA - Flooding Experiments with Blocked Arrays, Evaluation Report," KFK, 3657, March 1984, and Donald M. Ogden, "Review of FEBA Blockage Data," NUREG/CR-0048 Vol. 1, 11th Water Reactor Safety Research meeting, USNRC 1983, which indicate that omission of a pre-rupture swelling flow diversion model in FTI LOCA methodologies would not be non-conservative for calculated pre-rupture clad swelling of up to about 57 percent. Based on this information, the staff concludes that the previous limit of 20 percent cladding swell for FTI LOCA methodologies may be raised to 57 percent, and that a clad swelling flow diversion model may be omitted in LOCA analyses with FTI LOCA methodologies for calculated pre-rupture clad swelling of up to 57 percent. Above 57 percent pre-rupture clad swelling, the user must justify the acceptability.

The sensitivity studies performed demonstrated calculational stability and yielded expected results. The M5 calculated LOCA transient behavior showed modest quantitative differences from that of Zr-4, but the calculated behavior for LOCA transients with the two fuel types was very similar qualitatively.

In letters dated April 23 and September 24, 1999, Framatome also discussed the mechanics of incorporating correlations to accommodate M5 into its LOCA analysis codes and evaluation models. The staff finds that these are in accordance with regulatory guidance. The staff reviewed the RELAP5/MOD2-B&W model changes that reflect the properties of M5 fuel, and found them to be acceptable. The other changes to the model, which are not used in licensing calculations, are outside the scope of this review.

In its review of BAW-10227P, the staff considered each of the cladding property effects as a functional input to the analytical model and finds them acceptable (as is described in other sections of this SE).

The staff also considered LOCA analyses for M5-clad fuel co-resident with Zircaloy-clad fuel considering the possible effects of the differences in cladding properties, especially fuel swelling and rupture differences. The staff concluded that, because of the close similarity of M5 to Zircaloy, the effects of the differences on neighboring bundles would not be significant as long as the bundle geometries, including fuel dimensions and material surfaces, were alike. The staff, therefore, finds that when M5-clad fuel is co-resident with Zircaloy fuel, and fuel geometry and other properties that might affect fluid dynamics are alike, no mixed core penalty needs to be factored into the LOCA analyses performed with FCF's LOCA models for fuels clad with either M5 or Zircaloy.

The NRC staff concludes that the modifications to the use of the FCF SBLOCA and LBLOCA methodologies with M5 cladding and thimble tubes are in conformance with the requirements of 10 CFR Part 50, Appendix K and are, therefore, acceptable. The limitations and conditions identified in past SEs for the Framatome SBLOCA and LBLOCA models continue to apply.

8.0 CONCLUSIONS

The NRC staff has reviewed the FCF's advanced cladding and structural material, M5, for PWR fuel mechanical designs described in BAW-10227P. The NRC staff concludes that the M5 properties and mechanical design methodology, as defined in BAW-10227P and References 5, 6, 7, 8, and 9, are in accordance with SRP Section 4.2, 10 CFR 50.46, and 10 CFR Part 50 Appendix K and, therefore, are acceptable for fuel reload licensing applications up to rod average burnup levels of 62,000 MWd/MTU and 60,000 MWd/MTU for Mark B and Mark-BW fuel designs, respectively.

9.0 REFERENCES

1. Framatome Cogema Fuels. September 1997. Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel. BAW-10227P, Framatome Cogema Fuels, Lynchburg, Virginia, transmitted by letter, J. H. Taylor (FCF) to U.S. NRC Document Control Desk, "Submittal of Topical Report BAW-10227P, Evaluation of Advanced Cladding and Structural Material in PWR Reactor Fuel," dated September 30, 1997, JHT/97-36.

2. B&W Fuel Company. June 1997. Extended Burnup Evaluation. BAW-10186P-A, B&W Fuel Company, Lynchburg, Virginia.

3. Letter, J. L. Birmingham, NRC, to C. F. McPhatter, Framatome Cogema Fuels, Request for Additional Information for Topical Report BAW-10227P, "Evaluation of Advanced Cladding and Structural Material in PWR Reactor Fuel," October 26, 1998.

4. Letter, J. L. Birmingham, NRC, to C. F. McPhatter, Framatome Cogema Fuels, Request for Additional Information for Topical Report BAW-10227P, "Evaluation of Advanced Cladding and Structural Material in PWR Reactor Fuel," January 29, 1999.

5. Letter, T. A. Coleman, Framatome Cogema Fuels, to U.S. NRC Document Control Desk, GR99-031.doc, February 5, 1999.

6. Letter, T. A. Coleman, Framatome Cogema Fuels, to U.S. NRC Document Control Desk, GR99-089.doc, April 23, 1999.

7. Letter, T. A. Coleman, Framatome Cogema Fuels, to U.S. NRC Document Control Desk, GR99-156.doc, July 29, 1999.

8. Letter, T. A. Coleman, Framatome Cogema Fuels, to U.S. NRC Document Control Desk, GR99-194.doc, September 24, 1999.

9. Letter, T. A. Coleman, Framatome Cogema Fuels, to U.S. NRC Document Control Desk GR-99-212.doc, October 20, 1999.

10. U.S. Nuclear Regulatory Commission. July 1981. "Section 4.2, Fuel System Design." Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants - LWR Edition. NUREG-0800, Rev. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

11. United States Federal Register. "Appendix A, General Design Criteria for Nuclear Power Plants." In 10 Code of Federal Regulations (CFR), Part 50. U.S. Printing Office, Washington, D.C.

12. United States Federal Register. "Reactor Site Criteria." In 10 Code of Federal Regulations (CFR), Part 100. U.S. Printing Office, Washington, D.C.

13. United States Federal Register. In 10 Code of Federal Regulations (CFR), Part 50.46. U.S. Printing Office, Washington, D.C.

14. B&W Fuel Company. October 1999. Safety Criteria and Methodology for Acceptable Cycle Reload Analyses. BAW-10179P-A, Revision 3, B&W Fuel Company, Lynchburg, Virginia.

15. Lusternik V. E., Peletsky V. E., and Petrova I. I. 1993, "Experimental Study of Calorific Properties of Materials with Zirconium Base (Alloy E110) Used for Reactors," Teplofiz.Vys. Temp., Volume 31, No.4, pp. 560-564.

16. Lusternik V. E., Peletsky V. E., and Petrova I. I. 1993, "High Temperature Calorimetric Measurements of Zr-0.01Nb Alloy at Various Rates of Heating," High Temperatures -- High Pressures, Volume 25, pp. 539-543, Presented at the 13th European Conference on Thermophysical Properties Lisboa, Portugal, August 30- September 3, 1993.

17. Lusternik V. E., and Petrova I. I. 1997, "Investigation of the Thermophysical Properties of the Alloy Zr-0.01Nb by a Subsecond Pulse-Heating Technique," High Temperatures -- High Pressures, Volume 29, pp 373-378.

18. American Society of Mechanical Engineers. 1983 Edition. "Section III, Nuclear Power Plant Components." ASME Code. American Society of Mechanical Engineers, New York.

19. Garde, A. M. September 1986. Hot Cell Examination of Extended Burnup Fuel from Fort Calhoun. DOE/ET/34030-11, CEND-427, Combustion Engineering, Inc., Windsor, Connecticut.

20. Newman, L. W. et al. 1986. The Hot Cell Examination of Oconee Fuel Rods After Five Cycles of Irradiation. DOE/ET/34212-50 (BAW-1874), Babcock & Wilcox, Lynchburg, Virginia.

21. Garde, A. M. 1989. "Effects of Irradiation and Hydriding on the Mechanical Properties of Zircaloy-4 at High Fluence." In Zirconium in the Nuclear Industry: Eighth International Symposium, ASTM STP 1023, pp. 548-569, Eds. L.F.P. VanSwam and C. M. Eucken. American Society for Testing and Materials, Philadelphia, Pennsylvania.

22. Wesley, D. A., and K. J. Firth. October 1989. TACO-3 Fuel Pin Thermal Analysis Code. BAW-10162P-A, Babcock & Wilcox, Lynchburg, Virginia.

23. Wesley, D. A., D. A. Farnsworth and G. A. Meyer, July 1995. Fuel Rod Gas Pressure Criterion (FRGPC), BAW-10183P-A, B&W Fuel Company, Lynchburg, Virginia.

24. Garzarolli, F., H. Stehle, and E. Steinberg. 1996. "Behavior and Properties of Zircaloys in Power Reactors: A Short Review of Pertinent Aspects in LWR Fuel," ASTM 1295, pp. 12-32.

25. McGrath, M. A. 1998. "In-Reactor Creep Behavior of Zircaloy-2 Under Variable Loading Conditions," presented at the Annual Meeting on Nuclear Technology '98, The German Nuclear Society and The German Atomic Forum, Munchen Park Hilton, Munich Germany, May 26-28, 1998.

26. Framatome Technologies Incorporated. November 1992. RELAP5/MOD2-B&W - An Advanced Computer Program for Light Water Reactor LOCA and Non-LOCA Transient Analysis, BAW-10264P, Rev.1, Framatome Technologies Incorporated, Lynchburg, Virginia.

27. Hagrman, D. L., A. Reymann, and R. E. Mason. 1981. MATPRO-Version 11 (Revision 1): A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior, NUREG/CR-0497, Rev. 2, Prepared for the U.S. Nuclear Regulatory Commission by EG&G Idaho, Inc., Idaho Falls, Idaho.

28. Lanning D. D., C. E. Beyer, and C. L. Painter. 1997. FRAPCON-3: Modifications to Fuel Rod Material Properties and Performance Models for High Burnup Applications, NUREG/CR-6534, Volume 1 (PNNL-11513, Volume 1), Prepared for the U.S. Nuclear Regulatory Commission by Pacific Northwest National Laboratory, Richland, Washington.

29. O'Donnell, W. J., and B. F. Langer. 1964. "Fatigue Design Basis for Zircaloy Components." In Nuc. Sci. Eng. 20:1.

30. Miles, T., et. al., August 1995. Program to Determine In-Reactor Performance of B&W Fuel Cladding Creep Collapse, BAW-10084P-A Rev. 3, B&W Fuel Company, Lynchburg, Virginia.

31. United States Federal Register. "Appendix K.I.A, ECCS Evaluation Models." In 10 Code of Federal Regulations (CFR), Part 50. U.S. Printing Office, Washington, D.C.

32. Powers, D. A., and R. O. Meyer. April 1980. Cladding, Swelling, and Rupture Models for LOCA Analysis. NUREG-0630, U.S. Nuclear Regulatory Commission, Washington, D.C.

33. U.S. Nuclear Regulatory Commission. 1974. Assumptions Used for Evaluating a Control Rod Ejection Accident for Pressurized Water Reactors, Regulatory Guide 1.77, U.S. Nuclear Regulatory Commission, Washington D.C.

34. Schmitz, F., et. al., March 1996. " New Results from Pulse Test in the CABRI Reactor," Proceedings of the 23rd Water Reactor Safety Information Meeting October 23-25,1995.

35. Fuketa, T., et. al., March 1996. "New Results from the NSRR Experiments with High Burnup Fuel," Proceedings of the 23rd Water Reactor Safety Meeting, October 23-25, 1995.

36. Chapman, R. H. June 1978. Multirod Burst Test Program Progress Report for July-December 1977, NUREG/CR-0313, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

37. Chapman, R. H. June 1979. Multirod Burst Test Program Progress Report for July-December 1978, NUREG/CR-00655, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

38. Chapman, R. H. November 1979. Multirod Burst Test Program Progress Report for April-June 1979, NUREG/CR-1023, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

39. Letter, A. C. Thadani, NRC, to J. M. Taylor, Babcock and Wilcox Nuclear Technologies, Acceptance for Referencing of Licensing Topical Report BAW-10166P, Revision 2, "BEACH - Best Estimate Analysis Core Heat Transfer, A Computer Program for Reflood Heat Transfer During LOCA," August 13, 1990.

Principal Contributors: S. L. Wu
F. R. Orr

Date: February 4, 2000