Enclosure

TECHNICAL EVALUATION REPORT

TECHNICAL EVALUATION REPORT OF TOPICAL REPORT CEN-396-P (VERIFICATION OF THE ACCEPTABILITY OF A 1-PIN BURNUP LIMIT OF 60 MWd/kg FOR ST. LUCIE UNIT 2)

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1.0 INTRODUCTION

The Florida Power and Light Company (FP&L) has requested the U.S. Nuclear Regulatory Commission (NRC) to review the Combustion Engineering, Inc. (C-E) topical report CEN-396-P for approval (Reference 1). This topical report provides justification for St. Lucie Unit 2 to achieve rod-average fuel burnup levels up to 60 MWd/kgM for C-E 16x16 fuel reloads. In addition, C-E intends to use this topical report to justify the C-E 16x16 fuel design reloads in other C-E plants to achieve rod-average fuel burnups up to 60 MWd/kgM if those applications meet the fuel design criteria defined in Reference 1. The analysis methods and design criteria used for this submittal for St. Lucie Unit 2 are also presented in Reference 1. Consequently, this review and resulting Technical Evaluation Report (TER) is the same as the review and NRC approval for Arkansas Nuclear One Unit 2 (ANO-2) (References 2 and 3) except for the issue of cladding oxidation [see Section 3.0(E) of this report] which was addressed in a reactor specific manner for ANO-2. Consequently, this TER references the same questions and ANO-2/C-E responses to the questions provided in the Safety Evaluation Report (SER) of ANO-2 (Reference 3) with the exception of an additional question addressed to FP&L on cladding oxidation [see Section 3.0(E) of this report for a further discussion of cladding oxidation in St. Lucie Unit 2].

Presented in this report is a review of the C-E mechanical design criteria, and analysis methods and results for the St. Lucie Unit 2/C-E 16x16 fuel design application. This review was conducted to assure that when the design criteria/limits are met they will prevent fuel damage or failure and maintain fuel coolability, as defined in the Standard Review Plan (SRP) (Reference 4), up to rod-average burnups of 60 MWd/kgM.

This review was based on the licensing requirements identified in Section 4.2 of the SRP (Reference 4). The objectives of this fuel system safety review, as described in Section 4.2 of the SRP, are to provide assurance that 1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), 2) the number of fuel rod failures is not underestimated for postulated accidents, 3) fuel system damage is never so severe as to prevent control rod insertion when it is required, and 4) coolability is always maintained. A "not damaged" fuel system is defined as one wherein fuel rods do not fail, fuel system dimensions remain within operation tolerances, and functional capabilities are not reduced below those assumed in the safety analyses. Objective 1, above, is consistent with General Design Criterion (GDC) 10 (10 CFR 50, Appendix A) (Reference 5), and the design limits that accomplish this are called specified acceptable fuel design limits (SAFDLs). "Fuel rod failure" (Objective 2) means that the fuel rod leaks and that the first fission product barrier (the cladding) has, therefore, been breached. Fuel rod failures must be accounted for in the dose analysis required by 10 CFR 100 (Reference 6) for postulated accidents. The general requirements to maintain control rod insertability (Objective 3) and core coolability (Objective 4) appear repeatedly in the GDC (e.g., GDC 27 and 35). Specific coolability requirements for the loss-of-coolant accident (LOCA) are given in 10 CFR 50, Section 50.46 (Reference 7). "Coolability," which is sometimes termed "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 even after a severe accident.

In order to assure that the above stated objectives are met and follow the format of Section 4.2 of the SRP, this review covers 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 is applied to postulated accidents. Specific fuel damage or failure mechanisms are identified under each of these categories in Section 4.2 of the SRP and these individual mechanisms are addressed in this report. The C-E design criteria, and analysis methods and results for the 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM, will be discussed in this report under each fuel damage or failure mechanism.

Pacific Northwest Laboratory (PNL) has acted as a consultant to the NRC in this review of Reference 1 and the previous review for ANO-2 (Reference 2). As a result of the review of Reference 2 by the NRC staff and their PNL consultants, a list of questions were sent by the NRC to ANO-2 (Reference 8) requesting further justification on why low measured cladding ductilities, greater cladding oxidation, guide wear, cladding collapse, and axial assembly growth are not limiting at the burnup level requested. ANO-2 provided responses to these questions in References 9 and 10. The responses submitted by ANO-2 in Reference 3 were jointly developed by ANO-2 and C-E staff and, therefore, will be referred to as ANO-2/C-E responses. The ANO-2/C-E responses in References 9 and 10 are applicable to St. Lucie Unit 2, with the exception of cladding oxidation, because this was identified as a reactor-specific issue in NRC's approval (Reference 3) of Reference 2. The design criteria and analyses submitted by FP&L in support of the license submittal for St. Lucie Unit 2 are those defined in Reference 1 by C-E and, therefore, will be referred to as C-E design criteria and analyses. As noted earlier, an additional question was sent by NRC to FP&L (Reference 11) concerning cladding oxidation in St. Lucie Unit 2 up to the burnup level requested.
FP&L/St. Lucie Unit 2 has provided a written response in Reference 12 and additional verbal responses were received from FP&L and C-E in a June 21, 1991 conference call.

The C-E 16x16 design description is briefly discussed in the following section (Section 2.0). The fuel damage and failure mechanisms and C-E analyses of these mechanisms are addressed in Sections 3.0 and 4.0, respectively, while fuel coolability is addressed in Section 5.0.

2.0 FUEL SYSTEM DESIGN

The C-E 16x16 fuel design discussed in the subject topical report has not changed from that described previously in Reference 13, therefore, the reader is directed to this earlier report for a design description.

3.0 FUEL SYSTEM DAMAGE

The design criteria presented in this section should not be exceeded during normal operation, including AOOs. Under each damage mechanism, there is an evaluation of the design criteria analysis methods and analyses used by C-E to demonstrate that fuel damage does not occur for the 16x16 design during normal operation, including AOOs, up to a rod-average burnup of 60 MWd/kgM.

(A) STRESS

Bases/Criteria - In keeping with the GDC 10 SAFDLs, fuel damage criteria for stress should ensure that fuel system dimensions remain within operational tolerances for normal operation and AOOs, and that functional capabilities are not reduced below those assumed in the safety analysis. The C-E design basis for fuel assembly, fuel rod, burnable poison rod, and upper-end fitting spring stresses is that the fuel system will be functional and will not be damaged due to excessive stresses (References 14 and 15).

The C-E stress criteria for the fuel assembly components are provided in References 13 and 16. The design limit for fuel rod and burnable poison rod cladding is that the maximum primary tensile stress is less than two-thirds of the Zircaloy yield strength as affected by temperature.

The design limit of the Inconel X-750 upper-end fitting spring is that the calculated shear stress will be less than or equal to the minimum yield stress in shear.

Many of these bases and limits are used by the industry at large. C-E has employed various conservatisms in the limits such as the use of unirradiated yield strengths for zirconium-based alloys. The NRC has previously concluded (Reference 15) that the fuel assembly, fuel rod, burnable poison rod, and upper-end fitting spring stress design bases and limits were acceptable for rod-average burnup levels up to 52 MWd/kgM. Extending the burnup level to 60 MWd/kgM does not reduce the applicability of these criteria and, thus, PNL concludes that these criteria are acceptable for use in the current application to the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - C-E has stated that the methods used to perform stress analyses will not change from those used and approved for previous applications. These analyses are performed using conventional engineering formulas from standard engineering mechanics textbooks and performed in accordance with ASME general guidelines for analyzing primary and secondary stresses. The NRC has concluded (Reference 15) that these stress analyses are acceptable for rod-average burnup levels up to 52 MWd/kgM. Extending the rod-average burnup level to 60 MWd/kgM does not reduce the applicability of these methods and, thus, PNL concludes that these analysis methods are acceptable for application to the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM. As noted in Section 3.0 (E), stress analyses at extended burnup levels are required to include the effects of cladding thinning due to cladding oxidation.

(B) DESIGN STRAIN

Bases/Criteria - With regard to fuel assembly design strain, the C-E design basis for normal operation and AOOs is that permanent fuel assembly deflections shall not result in control element assembly (CEA) insertion time beyond that allowable. This basis is satisfied by adherence to the stress criteria mentioned above and strain criterion yet to be discussed.

The submitted topical report provides a design criterion for fuel rod and burnable poison rod cladding uniform circumferential strain (elastic plus plastic) of one percent (1%) as a means of precluding excessive cladding deformation. This strain criterion is consistent with that given in Section 4.2 of the SRP.

The material property that could have a significant impact on the cladding strain criterion at the requested extended burnup levels is cladding ductility. The strain criterion could be impacted if cladding ductility were decreased, as a result of extended burnup operations, to a level that would allow cladding failure without the 1% cladding strain criterion being exceeded in the C-E analyses. Recent measured cladding and plastic cladding strain values from C-E fuel rods (Reference 17) and other pressurized-water reactor (PWR) fuel vendors (Reference 18) have shown a decrease in cladding ductilities when local burnups exceed 52 MWd/kgM. The cladding plastic strain values decreased to 0.03 to 0.11% when local burnups were between 55 and 63 MWd/kgM.

ANO-2/C-E was questioned on whether these significant reductions in cladding plastic ductilities justified a decrease in the 1.0% design criterion for total uniform strain (elastic plus plastic) for C-E fuel with local burnups greater than 55 MWd/kgM (Reference 8). ANO-2/C-E responded (Reference 9) that because of the increase in the yield strength and the corresponding increase in elastic strain of the cladding due to irradiation, the typical elastic strains were above 1% using nominal values for irradiated yield strength and Young's modulus at burnups greater than 55 MWd/kgM. ANO-2/C-E was further questioned in a conference call about the probability that the combined elastic plus plastic strains between 55 and 63 MWd/kgM would fall below the 1% strain criterion. ANO-2/C-E presented (Reference 10) a statistical analysis of their measured yield strength data from cladding with local burnups greater than 55 MWd/kgM and calculated a tolerance limit about the mean value for yield strength. They also calculated a tolerance limit about the mean value for Young's modulus using data from the open literature. Using the lower bound tolerance limit for yield strength and the upper bound tolerance limit for Young's modulus plus the range of plastic strain, they calculated that there is a 9% probability that cladding strain would fall below the 1% total limit for a strain limit at burnups greater than 55 MWd/kgM.

PNL has performed an independent simplified statistical analysis using a one-sided lower tolerance limit at a 7% probability level of the measured yield strengths at burnups greater than 55 MWd/kgM and a one-sided upper tolerance limit at a 7% probability level of the measured values for Young's modulus. Dividing the lower tolerance limit for yield strength by the upper tolerance limit for Young's modulus it is calculated that there is slightly greater than a 7% probability that cladding strain will fall below the 1.0% total uniform strain limit at local burnups between 55 and 63 MWd/kgM. The 7% probability of falling below the 1.0% strain limit calculated is conservative because this simplified approach has assumed that combining the yield strength and Young's modulus tolerance limits will result in an equivalent plastic strain tolerance

limit. Hall and Sampson (Reference 19) have provided a more exact analytical procedure for determining either one-sided or two-sided tolerance limits for the distribution of the quotient (e.g., plastic strain) of two independent normal variables (e.g., yield strength and Young's modulus) for this application. This more exact analytical procedure results in less than a 7% probability of falling below the 1.0% strain limit at local burnups between 55 and 63 MWd/kgM.

Therefore, because 1) there is a low probability of total uniform strain falling below 1% in the C-E 16x16 fuel cladding, 2) conservative power histories are used in the C-E strain analysis, and 3) no fuel failures have been observed on fuel rods irradiated with rod-average burnups to 63 MWd/kgM, PNL concludes that the 1% total uniform strain limit remains applicable for the C-E 16x16 fuel design in St. Lucie Unit 2 up to a rod-average burnup of 60 MWd/kgM. However, PNL recommends that future requests to extend the rod-average burnup limit beyond 60 MWd/kgM should be accompanied with measured cladding strain, and yield and fracture strength data at the extended burnup levels requested. This data is necessary to demonstrate that the total uniform strain criterion of 1% remains applicable at these higher burnups and that fuel cladding brittle fracture will not occur during normal operation and AOOs at these higher burnups.

Evaluation - C-E utilizes the FATES3B (Reference 20) computer code to predict cladding strain and other fuel performance phenomena at high burnup levels. This code has been approved by the NRC for fuel performance analyses up to rod-average burnups of 60 MWd/kgM (Reference 21). The FATES3B code will take the place of the earlier FATES3 code (Reference 22). Therefore, PNL concludes that the use of the FATES3B code for calculating cladding strain for the C-E 16x16 fuel design in St. Lucie Unit 2 is acceptable for rod-average burnups up to 60 MWd/kgM.

(C) STRAIN FATIGUE

Bases/Criteria - The C-E strain fatigue criterion is different from those described in Section 4.2 of the SRP, i.e., a safety factor of 2 on stress amplitude or of 20 on the number of cycles using the methods of O'Donnell and Langer (Reference 23). Instead, C-E has proposed, in the past, that the cumulative strain cycling usage (i.e., the sum of the ratios of the number of cycles in a given effective strain range to the permitted number in that range) will not exceed 0.8. For Zircaloy cladding, the design limit curve has been adjusted to provide a strain margin for the effects of uncertainty and irradiation. The resulting curve given in References 13 and 14 bounds all of the data used in the development of the criterion that is discussed in the SRP. The NRC has previously concluded that the proposed criterion was acceptable for current burnup levels (Reference 15).

The material property that could have a significant effect on the strain fatigue criterion is cladding ductility. As discussed in the above section for design strain, extended burnup operation above local burnups of 55 MWd/kgM results in a significant reduction in cladding ductilities. However, as also discussed herein, there is a low probability that cladding ductility will fall below the acceptable limit for total uniform strain at a rod-average burnup of

60 MWd/kgM. In addition, there is a considerable amount of conservatism in the C-E strain fatigue analysis methodology. Therefore, PNL concludes that the strain fatigue criterion proposed in Reference 1 is acceptable for licensing applications to C-E 16x16 fuel in St. Lucie Unit 2 up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The fuel and cladding models used to determine fuel and cladding diametral strain for the fatigue analysis are those in the FATES3B code (Reference 20) which has been approved by the NRC (Reference 21). The power history used for the fatigue analysis includes conservative estimates of daily power cycling and AOOs and has been described previously in Reference 14. This analysis also accounts for a conservative number of hot and cold shut-downs during the fuel lifetime. This power history takes into account the extra duty required for rod-average burnups up to 60 MWd/kgM. Therefore, PNL concludes that the C-E strain fatigue analysis models referenced are acceptable for application to the C-E 16x16 fuel design in St. Lucie Unit 2 up to a rod-average burnup of 60 MWd/kgM.

(D) FRETTING WEAR

Bases/Criteria - Fretting wear is a concern for fuel and burnable poison rods, and the guide tubes. Fretting 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 spacer spring loads in combination with small amplitude, flow-induced, vibratory forces. Guide tube wear may result when there is flow-induced vibration between the control rod ends and the inner wall of the guide tubes.

While Section 4.2 of the SRP does not provide numerical bounding value acceptance criteria for fretting wear, it does stipulate that the allowable fretting wear should be stated in the safety analysis report and that the stress/strain and fatigue limits should presume the existence of this wear.

The submitted topical report has addressed fuel and burnable poison rod fretting wear by referring to Reference 14 and stating that no significant wear has been observed for C-E fuel rods and no additional fretting wear was expected due to the extension of rod-average burnup level to 60 MWd/kgM. Indicated in Reference 14 is that a specific fretting wear limit was not used for C-E fuel assembly components, because it has not been a problem for current C-E fuel designs. This same argument was used to explain why fretting wear was not accounted for in the fuel and burnable poison rod analyses for cladding stress and fatigue. In order to support this claim, in the previous review (Reference 15), C-E provided fuel examination information from 744 assemblies with average burnups up to approximately 52 MWd/kgM that showed no failures or significant wear on the surface of their fuel or burnable poison rods. It is noted that since this time, C-E has performed a visual examination of 14x14 designed fuel rods irradiated to rod-average burnups up to 56 MWd/kgM and found no surface anomalies other than minor scratches (Reference 17).

Because of the lack of significant fretting wear in the examination of more than 744 C-E fuel assemblies, with rod-average burnups to 56 MWd/kgM and existing fuel surveillance programs, PNL concludes that C-E has demonstrated

that fretting wear in their fuel and burnable poison rods will be acceptable up to rod-average burnups of 60 MWd/kgM.

Guide tube wear, however, was observed in several C-E fuel assemblies in 1977. Since then a design change in the guide tubes has greatly reduced guide tube wear for both 14x14 and 16x16 fuel assembly designs. However, it was noted in the NRC review of Reference 14 that very limited low burnup data were available for this new guide tube design (Reference 15). ANO-2/C-E was requested (Reference 8) to provide guide tube wear data for the new unsleeved guide tube design to be used in the subject reload and future C-E 16x16 plant reloads and compare this data to their maximum predicted wear correlation. ANO-2/C-E provided (Reference 9) this comparison, which demonstrated that the measured wear data is a factor of 3 below the C-E correlation for maximum wear for both 14x14 and 16x16 fuel assembly designs. However, it should be noted that the maximum in-reactor operating times of the wear data are only one-third of those expected for rod-average burnups to 60 MWd/kgM. The ANO-2/C-E response (Reference 9) argued that this lack of wear data at the maximum burnup level requested was satisfactory because 1) the C-E maximum guide tube fretting wear correlation is very conservative, and 2) there is a large margin between maximum predicted fretting wear at the maximum burnup level requested and the minimum amount of allowable wear that a guide tube can sustain without violating any design criteria.

Due to the conservative nature of the C-E guide tube fretting wear correlation and the large margin that exists before design criteria are violated, PNL concludes that guide tube wear in the C-E 16x16 fuel design is acceptable up to a rod-average burnup level of 60 MWd/kgM.

Evaluation - The St. Lucie Unit 2/C-E submittal has suggested that the lack of a large amount of measured fretting wear in C-E fuel and burnable poison rods supports their conclusion that they do not need to include the effects of cladding thinning due to fretting wear in their stress, strain, and fatigue analyses for the fuel and burnable poison rods. However, this does not answer the question of what the calculated impact of a small reduction in cladding thickness has on safety and design analyses, e.g., LOCA and stress/strain. In the past, C-E (Reference 14) has indicated that the most limiting LOCA analysis is early-in-life when stored energy is the highest and fretting wear is insignificant for this analysis. PNL agrees with this assessment. ANO-2/C-E also responded to a question on cladding thinning due to oxidation by stating that they conservatively reduce the cladding thickness of the 16x16 fuel rods by 3 mils in their stress analysis [see Section 3.0(E)]. This inclusion of cladding thinning due to corrosion is judged to bound thinning due to fretting wear because corrosion is the greater of the two thinning mechanisms for C-E's current fuel designs and because these two mechanisms do not occur simultaneously at the same location on a fuel rod. For example, where fretting wear is present on the fuel or burnable poison rod, oxidation will not be present and vice versa. Therefore, PNL concludes that cladding thinning of the fuel and burnable poison rods due to fretting wear are bounded by C-E's analysis of cladding thinning due to oxidation.

As noted in the "Criteria" section, guide tube wear has been a problem in the past for C-E assemblies. Design changes to reduce guide tube wear have been

implemented by C-E for both 14x14 and 16x16 assemblies. Both out-of-reactor and in-reactor confirmation tests have been performed to show that these design changes have resulted in a significant decrease in guide tube wear for in-reactor residence times that are one-third of those expected for an extended burnup level of 60 MWd/kgM. Extrapolating the guide tube wear to the in-reactor residence time expected for an extended rod-average burnup level of 60 MWd/kgM has demonstrated that guide tube wear will remain at a relatively low level. PNL concludes that guide tube wear is not expected to be a problem up to a rod-average burnup of 60 MWd/kgM for the newly designed guide tubes in the C-E 16x16 design in St. Lucie Unit 2 (based on the low level of wear at lower burnups). PNL recommends that the licensee continue to examine guide tubes up to the extended burnup levels requested to confirm that wear is not a problem at these burnup levels.

(E) OXIDATION AND CRUD BUILDUP

Bases/Criteria - Section 4.2 of the SRP identifies cladding oxidation and crud buildup as potential fuel system damage mechanisms. General mechanical properties of the cladding are not significantly impacted by thin oxides or crud buildup. The major means of controlling fuel damage due to cladding oxidation and crud is through water chemistry controls, materials used in the primary system, and fuel surveillance programs that are all reactor specific. Because these controls are already included in the specific reactor design, a design limit on cladding oxidation and crud is considered to be redundant and, thus, not necessary.

This does not, however, eliminate the need to include the effects of cladding oxidation and crud in thermal and mechanical licensing analyses as per Section 4.2 of the SRP. This issue is of particular concern for extended burnup operation in those reactors that have shown high levels of cladding corrosion at lower burnup levels. This will be discussed in further detail in the evaluation presented below.

Evaluation - The amount of cladding oxidation expected for a particular reactor is dependent on fuel rod powers (surface heat flux), chemistry controls and primary inlet coolant temperatures used by that reactor, but the amount of oxidation increases with in-reactor residence time and can not be eliminated. Therefore, extending the rod-average burnup level to 60 MWd/kgM could result in 1) thicker oxide layers that provide an extra thermal barrier that increases cladding and fuel temperatures, and 2) cladding thinning that can affect the mechanical analyses. The degree of this effect on thermal and mechanical analyses is dependent on reactor coolant temperatures and the level of success of a reactors' chemistry controls.

The St. Lucie Unit 2/C-E submittal (Reference 1) has provided oxide thickness measurements from fuel rod cladding irradiated in ANO-2 near the burnup level requested and placed a conservative upper bound 3σ (standard deviation) limit on the measured values. The NRC questioned FP&L (Reference 11) on the applicability of the ANO-2 cladding oxidation data to St. Lucie Unit 2 with respect to those reactor specific parameters that impact cladding corrosion. FP&L has responded (Reference 12) that cladding temperatures in St. Lucie Unit 2 are lower than for ANO-2 due to lower coolant temperature and core average rod powers but that lithium levels in the coolant of St. Lucie Unit 2 are greater. These two parameters have opposing effects on cladding corrosion; i.e., lower cladding temperatures decrease corrosion but higher lithium levels have been shown to increase corrosion by a small amount. Consequently, FP&L has concluded (Reference 12) that while it is likely that corrosion in St. Lucie Unit 2 will be similar to that in ANO-2 it is impossible to state that the ANO-2 cladding oxidation data base will bound St. Lucie Unit 2 cladding oxidation.

FP&L and C-E were further questioned in a conference call with NRC and PNL on June 21, 1991 on the maximum level of oxidation used for the thermal and mechanical analyses for C-E 16x16 fuel in St. Lucie Unit 2 and whether FP&L intends to monitor oxide thickness levels in St. Lucie Unit 2 in order to confirm that the maximum thickness level assumed by C-E is bounding. C-E responded that they used the maximum upper bound oxide thickness mentioned in Section 4.1.2.2.a of Reference 1 for the thermal analyses up to a rod-average burnup of 60 MWd/kgM. For their stress analyses, C-E stated that they reduced the as-fabricated cladding thickness by a proprietary percentage to account for cladding imperfections wear and oxidation. C-E has further stated that the results of both their thermal and mechanical analyses of the C-E 16x16 fuel in St. Lucie Unit 2 are within the stated criteria for satisfactory performance. PNL has reviewed the equivalent oxide thickness levels used by C-E for their stress and thermal analyses, and concludes that based on available data these thickness levels will bound the maximum oxide thickness for C-E 16x16 fuel in St. Lucie Unit 2 up to a rod-average burnup of 60 MWd/kgM. FP&L has also indicated that they intend to monitor cladding oxide thickness up to a rod-average burnup of 60 MWd/kgM in order to confirm that the oxide thickness and cladding thinning values used by C-E in their analyses are bounding for St. Lucie Unit 2. Therefore, PNL concludes that cladding oxidation is acceptable for the C-E 16x16 fuel design in St. Lucie Unit 2 up to a rod-average burnup of 60 MWd/kgM.

There is an indication that cladding corrosion may limit the fuel rod performance lifetime for higher burnup irradiations for specific plants. Because cladding oxidation is dependent on reactor-specific conditions such as reactor coolant temperatures and water chemistry it is necessary to examine cladding oxidation on a reactor-specific basis until C-E has a broad enough cladding corrosion data base to bound those reactor specific parameters that affect corrosion at extended burnups. Therefore, PNL recommends that future requests to extend the rod-average burnup limit beyond 60 MWd/kgM should be accompanied with reactor-specific corrosion data at the burnup levels requested.

(F) 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 placing design limits on the amount of bowing that is permitted, the effects of bowing are included in the safety analysis. This is consistent with the SRP and the NRC has approved this for current burnup levels (Reference 15). The methods used for predicting the degree of rod bowing at the extended burnups requested are evaluated below.

Evaluation - The C-E analysis methods used to account for the effect of fuel and poison rod bowing in 14x14 and 16x16 fuel assemblies are presented in Reference 14 and CENPD-225 (Reference 24) with its supplements. These methods have been approved by the NRC (References 15 and 24) for fuel and Type 3 poison rods to current burnup levels.

C-E has compared 14x14 rod bow data with burnups to 45 MWd/kgM to their licensing rod bow model (Reference 14) and demonstrated that the model becomes more conservative at higher burnups. These data appear to suggest that the rate of rod bow significantly decreases at burnups greater than 30 to 35 MWd/kgM, while the C-E analytical model for rod bow assumes little or no decrease in the rate of rod bowing with burnup. This results in very conservative predictions of rod bowing in C-E 14x14 designed fuel at high burnup levels. The C-E rod bowing model for 16x16 fuel rods was also demonstrated in Reference 14 to be very conservative by comparison to data with burnups up to 33 MWd/kgM. ANO-2 has indicated that they routinely perform visual examination of their fuel assemblies to provide assurances of satisfactory performance of their fuel. The phenomenon of rod bowing is generic to all LWRs even though design differences such as the length between spacers and rod diameter are important to the amount of rod bowing. Therefore, other fuel vendor experience with rod bowing is valuable in evaluating the trend in rod bowing at extended burnups.

FRAMATOME has measured rod bow on their FRAGEMA fuel assemblies for fuel burnups up to 53 MWd/kgM and found that the rate of rod bowing versus burnup decreases at burnups greater than 30 to 35 MWd/kgM (Reference 25). Similar measurements of rod bowing have been made by Kraftwerk Union AG (KWU) on their fuel designs up to burnups of 50 MWd/kgM (Reference 26) and found that due to the scatter in their limited data, the decrease in the rate of rod bowing was not as evident as that demonstrated in References 14 and 25. However, KWU did find that rod bowing was limited to gap closures of less than 40% on their fuel designs which is consistent with the data in Reference 14.

PNL concludes that the C-E analysis methods (Reference 24) applied to the C-E 16x16 fuel design in St. Lucie Unit 2 will remain conservative up to the extended burnup level requested and, therefore, are acceptable up to a rod-average burnup level of 60 MWd/kgM.

(G) AXIAL GROWTH

Bases/Criteria - The core components requiring axial-dimensional evaluation are the CEAs, burnable poison rods, fuel rods, and fuel assemblies. The CEAs are not included in this extended burnup review. The growth of burnable poison and fuel rods is mainly governed by a) the irradiation and stress-induced growth of the Zircaloy-4 cladding, and b) the behavior of poison, fuel, and spacer pellets, and their interaction with the Zircaloy-4 cladding. The growth of the fuel assemblies is a function of both the compressive creep and the irradiation-induced growth of the Zircaloy-4 guide tubes. For the Zircaloy cladding and fuel assembly guide tubes, the critical tolerances that require controlling are a) the spacing between the fuel rods and the upper fuel assembly fitting (i.e., shoulder gap), and b) the spacing between the fuel assemblies and the core internals. Failure to adequately design for the former may result in fuel rod bowing, and for the latter may result in collapse and failure of the assembly hold-down springs. With regard to inadequately designed shoulder gaps, problems have been reported (References 27, 28, 29, and 30) in foreign (Obrigheim and Beznau) and domestic (Ginna and ANO-2) plants that have necessitated predischarge modifications to fuel assemblies.

For burnable poison and fuel rods, C-E has a design basis that sufficient shoulder gap clearances must be maintained throughout the design lifetime of the fuel at a 95% confidence level. Similarly, for fuel assembly axial growth, C-E has a design basis that sufficient clearance must be maintained between the fuel assembly and the upper guide structure throughout the design lifetime of the fuel assembly at a 95% confidence level. This basis allocates a fuel assembly gap spacing, which will accommodate the maximum axial growth, when establishing the design minimum initial fuel assembly clearance with respect to the core internals. These design bases and limits dealing with axial growth prevent mechanical interference and, thus, have been approved by NRC for previous extended burnup levels (Reference 15). PNL concludes that these design bases and limits will ensure that contact is prevented and, thus, are found to be acceptable for the C-E 16x16 fuel design to 60 MWd/kgM.

Evaluation - The C-E methods and models used for predicting fuel rod and assembly growth in this submittal (Reference 1) have been changed somewhat from those previously approved in Reference 14 to better predict the new higher exposure growth data. This evaluation will discuss the new revised models used to predict fuel rod and assembly growth. Also presented is how C-E uses these revised models to predict 1) the shoulder gap spacings between the fuel rod and the upper fuel assembly fitting, and 2) the gap spacing between the fuel assembly and core internals.

The new revised fuel and burnable poison rod growth model is based on C-E 14x14 and 16x16 rod data with rod-average burnups above those requested. The model predicts a "best estimate" value of rod growth with uncertainties. The new revised assembly growth model is based on the SIGREEP computer code and growth data from assemblies with stress relief annealed (SRA) guide tubes with assembly average burnups below those requested in this submittal. The SIGREEP prediction of assembly growth takes into account the different axial stresses on the guide tubes for different C-E plant fuel assemblies including the St. Lucie Unit 2 assemblies and uses input parameters with assigned statistical uncertainties along with Monte Carlo random selection techniques and combinations of these uncertainties to obtain a probability density function of assembly growth at a given fluence (burnup) level.

The C-E evaluation of shoulder gap spacing uses the lower bound probability density function for assembly growth and the upper bound probability density function for rod growth with uncertainties in the SIGREEP computer code to predict the shoulder gap at an upper bound 95% probability with a 95% confidence level. This C-E methodology for predicting an upper bound 95/95 shoulder gap spacing has been compared to measured shoulder gap data (Reference 1) that have assembly-average burnups below those requested in this submittal. These C-E upper bound predictions do indeed bound the shoulder gap data and appear to become even more conservative at the higher burnup levels.

It should be noted that in the shoulder gap calculation the amount of fuel rod growth is much greater than the amount of assembly growth, therefore, the prediction of fuel rod growth dominates the analysis of shoulder gap spacing. It should also be noted that the C-E rod growth data have rod-average burnups greater than those requested in this submittal.

PNL concludes that the C-E analysis methodology is acceptable for application to the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM because 1) C-E has fuel rod growth data above the burnup level requested, 2) fuel rod growth dominates the shoulder gap spacing analysis, and 3) the large amount of conservative margin C-E has demonstrated in their prediction of shoulder gap spacing.

The C-E analysis of the gap spacing between the upper fuel assembly and core internals uses the SIGREEP probability density function for assembly growth to predict a minimum 95/95 value for this gap spacing in order to prevent bottoming out of the assembly hold-down springs. Because C-E does not have assembly growth data up to the burnup level requested, they were questioned (Reference 8) on the gap margin that exists at the burnup level requested in this submittal to prevent bottoming of the hold-down spring. ANO-2/C-E's response (Reference 9) indicated that there was approximately one-third of the original as-fabricated gap spacing left prior to bottoming out of the hold-down spring at the burnup requested. This same significant margin in gap spacing should exist for the C-E 16x16 fuel in St. Lucie Unit 2. Due to this significant margin and C-E's conservative analysis methodology, PNL concludes that bottoming out and failure of the hold-down spring due to fuel assembly growth is not expected for the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM. However, PNL recommends that St. Lucie Unit 2 visually examine the hold-down springs to confirm that there is significant margin of the compressibility of these springs in those assemblies discharged with rod-average burnups near or at the 60 MWd/kgM level.

(H) 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. Section 4.2 of the SRP presents a rod pressure limit that is sufficient to preclude fuel damage in this regard, and it has been widely used by the industry; it states that rod internal gas pressure should remain below the nominal system pressure during normal operation, unless otherwise justified. C-E has elected to justify a rod internal pressure limit above system pressure in Reference 31 and this proprietary rod pressure limit has been approved by NRC.

The C-E design criterion used to establish this proprietary rod pressure limit is: "The fuel rod internal hot gas pressure shall not exceed the critical maximum pressure determined to cause an outward cladding creep rate that is in excess of the fuel radial growth rate anywhere locally along the entire active length of the fuel rod." In addition, C-E has evaluated the impact of this rod pressure limit on hydride reorientation and accident analyses. Therefore, PNL concludes that the NRC approved rod pressure limit defined in Reference 31 is also acceptable for application to the C-E 16x16 fuel design to a rod-average burnup of 60 MWd/kgM.

Evaluation - C-E has indicated that they will use the FATES3B (Reference 20) computer code to calculate maximum rod internal pressures and this code has been approved by NRC in Reference 21. The FATES3B code has been verified against fission gas release data from a variety of fuel designs with rod-average burnups up to 60 MWd/kgM. The use of the approved FATES3B code is recommended over the earlier approved FATES3 code (Reference 22) because the former has been verified against a much larger data base at higher burnup levels.

ANO-2/C-E were questioned on the apparent small underprediction of fission gas release by the FATES3B code when fission gas release values were low (<3% release) at high burnup levels and the impact of this underprediction on licensing analyses. ANO-2/C-E responded that licensing analyses are typically performed in a conservative manner on the peak operating rod, i.e., a rod with high temperatures, high fission gas release, and high internal rod pressures and, therefore, the small underprediction in fission gas release at low temperatures were insignificant for licensing analyses. They also demonstrated that the amount of underprediction was small in terms of calculated internal rod pressures in these low temperature rods. PNL concurs with this assessment and concludes that the FATES3B code is acceptable for the analysis of internal rod pressures for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

In addition to the computer code, the input power history to the code is very important for the internal rod pressure calculation. Consequently, C-E has been required by NRC, in the past, to define a methodology for determining the power history for the rod pressure calculation. This methodology was first reviewed and approved for Reference 14 and C-E has provided an example of how this methodology is applied in Reference 1. Therefore, PNL concludes that the use of the approved FATES3B code along with the approved C-E power history methodology described in References 1 and 14 is acceptable for licensing applications for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

(I) ASSEMBLY LIFTOFF

Bases/Criteria - The SRP calls for the fuel assembly hold-down capability (wet weight and spring forces) to exceed worst-case hydraulic loads for normal operation, which includes AOOs. The NRC-approved C-E Extended Burnup Topical Report (Reference 14) has endorsed this design basis. PNL concludes that this design basis is also acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - C-E methodology for assembly liftoff analysis has been summarized in Reference 2 and approved by the NRC for current burnups in Reference 15. The fuel assembly liftoff force is a function of plant coolant flow, spring forces, and assembly dimensional changes. Extended burnup irradiation will result in additional hold-down spring relaxation and assembly length increases which will have opposing effects on the assembly hold-down force, i.e., the

length increase will compress the spring and, therefore, increase the hold-down force. Industry experience has demonstrated that the assembly length increase due to irradiation more than compensates for spring relaxation so that the hold-down force increases with increased burnup. In fact, a major concern at extended burnups is that the assembly length change will compress the spring to the extent that it will bottom out and break. This issue has been addressed satisfactorily in Section 3.0(G), "Axial Growth." Consequently, PNL concludes that the issue of assembly liftoff has been satisfactorily addressed for the C-E 16x16 fuel design to a rod-average burnup of 60 MWd/kgM.

(J) CONTROL MATERIAL LEACHING

Bases/Criteria - The SRP and GDC require that reactivity control be maintained. Rod reactivity can sometimes be lost by leaching of certain poison materials if the cladding of control-bearing material has been breached.

Evaluation - Reactivity loss from burnable poison rods at extended burnup levels is found to be insignificant because nearly all of the reactivity controlling boron-10 is burned out at these burnup levels. Consequently, reactivity loss due to leaching of burnable poison rods at the extended burnup level requested is considered to be insignificant.

Control rod lifetimes are not changed in this submittal from those previously approved by the NRC and, therefore, are not affected by this request to extend fuel rod average burnups to 60 MWd/kgM. PNL concludes that the issue of control material leaching has been satisfactorily addressed for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

4.0 FUEL ROD FAILURE

In the following paragraphs, fuel rod failure thresholds and analysis methods for the failure mechanisms listed in the SRP are reviewed. When the failure thresholds are applied to 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 calculations required by 10 CFR 100. The basis or reason 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 that they are met are reviewed below.

(A) HYDRIDING

Bases/Criteria - Internal hydriding as a cladding failure mechanism is precluded by controlling the level of hydrogen impurities during fabrication. The moisture level in the uranium dioxide fuel is limited by C-E to a proprietary value less than 20 ppm, and this specification is compatible with the ASTM specification (Reference 32) which allows two micrograms of hydrogen per gram of uranium (i.e., 2 ppm). This is the same as the limit described in the SRP and has been found acceptable by NRC (Reference 15) and PNL concludes that it continues to be acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

External hydriding due to waterside corrosion is a possible reason for the observed ductility decrease at local burnups >55 MWd/kgM discussed in Section 3.0 (B). Garde (Reference 33) has recently proposed that the ductility decrease is due to a combination of hydride formation and irradiation damage at these high burnup levels. The issue of cladding ductility has already been discussed in Section 3.0 (B) of this TER and found to be acceptable for the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The issue of internal hydriding is not expected to be affected by an increase in rod-average burnup level because this failure mechanism is dependent on the amount of hydrogen impurities introduced during fuel fabrication. Fuel failures due to internal hydriding occur early in a fuel rods' lifetime and are not dependent on the length of irradiation. Because C-E limits the level of hydrogen impurities in their fuel fabrication process, PNL concludes that this methodology is acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

The major issue for external hydriding at extended burnup levels is an increase in hydriding that results in a decrease in cladding ductility reducing the threshold for cladding failure. The issue of decreased cladding ductility at the extended burnup level requested has already been discussed in Section 3.0(B) of this report and PNL concludes it is acceptable for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

(B) CLADDING COLLAPSE

Bases/Criteria - If axial gaps in the fuel pellet column were to occur due to densification, the cladding would have the potential of collapsing into this axial gap (i.e., flattening). Because of the large local strains that would result from collapse, the cladding is assumed to fail. It is a C-E design basis that cladding collapse is precluded during the fuel rod and burnable poison rod design lifetime. This design basis is the same as that in the SRP and has been approved by the NRC (Reference 15). PNL concludes that this design basis is also acceptable for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The longer in-reactor residence times associated with the burnup extension requested for FP&L fuel will increase the amount of creep of an unsupported fuel cladding. Extensive postirradiation evaluations (Reference 14) by C-E have not shown any evidence of cladding collapse or large local ovalities in their fuel designs. This is primarily the result of their use of prepressurized rods and stable (non-densifying) fuel in current generation designs.

In addition, C-E has performed several postirradiation examinations that have looked for axial gap formation in their modern fuel designs and concluded that the largest measured gaps are much smaller than those required to achieve cladding collapse for current C-E fuel designs at a rod-average burnup of 60 MWd/kgM (Reference 1). These C-E measured cold axial gaps have been

corrected to hot axial gaps in the fuel rod during in-reactor operation for the cladding collapse analysis. ANO-2/C-E has stated that the resulting hot gap used in the cladding collapse analysis is in excess of that expected at a 95% probability and a 95% confidence level based on a C-E statistical analysis of the hot gaps (Reference 9). This cladding collapse analysis has demonstrated that the C-E 16x16 cladding will not collapse at a rod-average burnup greater than 60 MWd/kgM. Therefore, ANO-2/C-E has proposed that they no longer be required to address cladding collapse for new cores or reload batches of the C-E 16x16 design unless design or manufacturing changes are introduced which would significantly reduce cladding collapse times for this fuel design. PNL concludes that this proposed approach is acceptable for future C-E cores or reload batches of the 16x16 design and recommends that the issue of cladding collapse be reevaluated should rod-average burnups exceed 60 MWd/kgM.

(C) OVERHEATING OF CLADDING

Bases/Criteria - The design limit for the prevention of fuel failures due to overheating is that there will be at least a 95% probability at a 95% confidence level that the departure from nucleate boiling ratio (DNBR) will not occur on a fuel rod having the minimum DNBR during normal operation and AOOs. This design limit is consistent with the thermal margin criterion in Section 4.2 of the SRP and, thus, has been found acceptable for application to C-E fuel designs (Reference 14). This design limit is not impacted by the proposed extension in burnup. Therefore, PNL concludes that this design limit remains acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - As stated in Section 4.2 of the SRP, adequate cooling is assumed to exist when the thermal margin criterion to limit the DNBR or boiling transition in the core is satisfied. The analysis methods employed to meet the DNBR design basis are provided in References 34 through 39. These analysis methods have been approved by NRC for current burnup levels and PNL concludes that they are also acceptable for application to the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM.

The impact of rod bowing on DNB for the C-E 16x16 design in ANO-2 has been addressed in Reference 35. PNL concludes that ANO-2/C-E has adequately addressed the issue of cladding overheating for the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM.

(D) OVERHEATING OF FUEL PELLETS

Bases/Criteria - As a second method of avoiding cladding failure due to overheating, C-E precludes centerline fuel pellet melting during normal operation and AOOs. This design limit is the same as given in the SRP and has been approved for use at current levels. PNL concludes that this design limit is also acceptable for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The design evaluation of the fuel centerline melt limit is performed with the approved C-E fuel performance code, FATES3B (Reference 20).

This code is also used to calculate initial conditions for transients and accidents. As noted earlier, the FATES3B code has been accepted for fuel performance calculations up to a rod-average burnup of 60 MWd/kgM (Reference 21).

In the C-E centerline melting analysis, the melting temperature of the UO_2 is assumed to be 5080°F unirradiated and is decreased by 58°F per 10 MWd/kgM. This relation has been almost universally adopted by the industry and has been previously accepted by the NRC (Reference 15). Recent UO_2 fuel melting data by Komatsu with burnups to 30 MWd/kgM have shown no discernible decrease in melting temperature with burnup, and a drop of approximately 20°F per 10 MWd/kgM for UO_2-20% PuO_2 with burnups up to 110 MWd/kgM (Reference 40). This demonstrates the conservatism employed by C-E in their fuel melting temperature analysis at extended burnup levels. Therefore, PNL concludes that the C-E analysis methods for fuel melting are acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

(E) EXCESSIVE FUEL ENTHALPY

Bases/Criteria - The SRP guidelines for a severe reactivity initiated accident (RIA) in a PWR, Section 4.2.II.A.2(f), state that for "all RIAs in a PWR, the thermal margin criteria (DNBR) are used in a fuel failure criteria to meet the guidelines of Regulatory Guide 1.77 (Reference 41) as it relates to fuel failure." C-E has adopted this criterion for fuel failure in addition to other more stringent criteria for RIAs (Reference 42).

Evaluation - The NRC approved analysis methods for evaluating RIAs in C-E plants is provided in Reference 42. PNL concludes that the approved analysis methods described in Reference 42 are still applicable to the burnup extension requested and, therefore, are acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

The steady-state fuel operational data that are input to the CEA ejection analysis from the FATES3B code are dependent on fuel burnups. As noted earlier, PNL concludes that the FATES3B code is acceptable for steady-state fuel performance applications for C-E 16x16 fuel up to the 60 MWd/kgM rod-average burnup level requested in this submittal.

(F) PELLET/CLADDING INTERACTION

Bases/Criteria - As indicated in Section 4.2 of the SRP, there are no generally applicable criteria for PCI failure. However, two acceptance criteria of limited application are presented in the SRP for PCI: 1) less than 1% transient-induced cladding strain, and 2) no centerline fuel melting. Both of these limits are used in C-E fuel designs [see Sections 3.0(B) and 4.0(D)] and PNL concludes that they are acceptable in this application.

Evaluation - As noted earlier, C-E uses the FATES3B code (Reference 20) to demonstrate that their fuel meets both the cladding strain and fuel melt criteria. This code has been found to be acceptable for these applications [see Sections 3.0(B) and 4.0(D)] and, therefore, PNL concludes that its use is acceptable for evaluating PCI failures for C-E 16x16 fuel designs up to a rod-average burnup of 60 MWd/kgM.

C-E has also presented PCI power ramping tests on fuel rods that are similar to their fuel designs up to rod-average burnups of approximately 48 MWd/kgM that demonstrate that the ramp terminal power level for fuel failure does not decrease with increased burnup. In addition, the maximum power capability of extended burnup fuel is reduced because of fissile material burnout; therefore, limiting the driving force for PCI failures. Consequently, PNL concludes that C-E 16x16 fuel designs have adequate PCI resistance up to a rod-average burnup of 60 MWd/kgM.

(G) CLADDING RUPTURE

Bases/Criteria - Zircaloy cladding will burst (rupture) under certain combinations of temperature, heating rate, and differential pressure; conditions that occur during a LOCA. While there are no specific design criteria in the SRP associated with cladding rupture, the requirements of Appendix K to 10 CFR Part 50 must be met as those requirements relate to the incidence of rupture during a LOCA; therefore, a rupture temperature correlation must be used in the LOCA emergency core cooling system (ECCS) analysis. These Appendix K requirements for cladding rupture are not impacted by the St. Lucie Unit 2 request to extend rod-average burnup to 60 MWd/kgM and, therefore, PNL concludes that these requirements remain applicable to C-E 16x16 fuel designs up to the burnup level requested.

Evaluation - An empirical cladding creep model is used by C-E to predict the occurrence of cladding rupture in their LOCA-ECCS analysis. The rupture model is directly coupled to the cladding ballooning and flow blockage models used in the NRC approved ECCS evaluation model described in Reference 43.

The C-E cladding rupture model is not affected by FP&L's request to extend their burnup limit. Therefore, PNL concludes that the C-E model for cladding rupture for LOCA-ECCS analyses is acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Another concern raised during previous high-burnup reviews (Reference 31) is that these higher burnups can result in fuel rod pressures that exceed system pressure and these higher fuel rod pressures can affect cladding rupture during a LOCA. For those C-E fuel reloads that have calculated peak rod pressures above system pressure, C-E has previously agreed (Reference 31) to reevaluate their LOCA-ECCS analyses to determine the most limiting LOCA conditions for these reloads. Therefore, PNL concludes that C-E has addressed the issue of fuel rod pressures exceeding system pressure on cladding rupture in the LOCA-ECCS analysis.

Those important parameters that are input to the rupture analysis that can be burnup dependent, such as rod pressures, fission gas release, fuel stored energy, and gap conductance are calculated with the NRC approved code FATES3B. As noted earlier, the FATES3B code has been verified with data up to rod-average burnups of 62 MWd/kgM and approved to 60 MWd/kgM. Therefore, PNL concludes that the use of the FATES3B code is acceptable for input to LOCA-ECCS analyses of the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM, as requested in this submittal.

(H) MECHANICAL FRACTURING

Bases/Criteria - Mechanical fracturing of a fuel rod could potentially arise from an externally applied force such as a hydraulic load or a load derived from core-plate motion. To preclude such failure, the applicant has stated (Reference 14) that fuel rod fracture stress limits shall be in accordance with the criteria given in Table 9-1 of CENPD-178, Revision 1 (Reference 44).

The review of CENPD-178, Revision 1 and the criteria given in Table 9-1 (Reference 44) has been completed and found acceptable by NRC for current burnup levels (Reference 15). The C-E fracture stress limits in Reference 45 are conservatively based on unirradiated Zircaloy properties and are judged to remain conservative up to a rod-average burnup of 60 MWd/kgM for the mechanical fracturing analysis. Consequently, PNL concludes that these criteria are also found to be acceptable for application to the C-E 16x16 design up to a rod-average burnup of 60 MWd/kgM. However, PNL recommends that future requests to extend the burnup beyond 60 MWd/kgM should be accompanied with measured cladding yield and fracture strength data to demonstrate that the rod fracture stress limits described in Reference 44 remain conservative up to the burnup level requested.

Evaluation - The mechanical fracturing analysis is done as a part of the seismic-LOCA loading analysis. A discussion of the seismic-LOCA loading analysis is given in Section 5.0(D) of this report.

5.0 FUEL COOLABILITY

For 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 for the severe damage mechanisms listed in the SRP are reviewed.

(A) FRAGMENTATION OF EMBRITTLED CLADDING

Bases/Criteria - The most severe occurrence of cladding oxidation and possible fragmentation during an accident is a result of a significant degree of cladding oxidation during a LOCA. In order to reduce the effects of cladding oxidation for a LOCA C-E uses an acceptance criteria of 2200°F on peak cladding temperature and a 17% limit on maximum cladding oxidation as prescribed by 10 CFR 50.46. PNL concludes that these criteria provided by C-E for the LOCA analysis are acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The NRC-approved cladding oxidation models in Reference 45 are used by C-E to determine that the above criteria are met, as a result of the LOCA analysis. These models are not affected by the proposed extended burnup operation; however, the steady-state operational input provided to the LOCA analysis is burnup dependent. As noted earlier, those burnup dependent parameters important to the LOCA analysis, such as stored energy, gap conductance, fission gas release, and rod pressures from steady-state operation, are provided by the FATES3B code (Reference 20). Also, as noted earlier, FATES3B is acceptable for providing input to the evaluation of LOCA up to the

requested rod-average burnup of 60 MWd/kgM. PNL concludes that the use of Reference 45 is also acceptable for evaluating cladding oxidation and fragmentation during a LOCA for the C-E 16x16 fuel up to the rod-average burnup level requested in this submittal.

(B) VIOLENT EXPULSION OF FUEL MATERIAL

Bases/Criteria - In a CEA 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 fuel cladding and the rod-bundle geometry and to provide significant pressure pulses in the primary system. To limit the effects of CEA ejection, Regulatory Guide 1.77 recommends that the radially-averaged energy deposition at the hottest axial location be restricted to less than 280 cal/g. C-E has adopted this enthalpy limit (Reference 42).

Evaluation - The CEA ejection analysis methods used by C-E are described in the NRC approved report in Reference 42. The CEA ejection analysis for St. Lucie Unit 2 utilizes the methods in Reference 42. In general, the most limiting assemblies in a CEA ejection accident are low burnup assemblies because these assemblies have the greatest power and enthalpy capability in the core. The maximum enthalpies for fuel at a rod-average burnup of 60 MWd/kgM will be significantly bounded by the low burnup assemblies because power capability of this high burnup fuel is low. Consequently, fuel at an extended burnup level of 60 MWd/kgM is expected to remain well below the 280 cal/g limit. PNL concludes that the analysis methods used by C-E for evaluating the CEA ejection accident are acceptable for application to the C-E 16x16 fuel up to a rod-average burnup of 60 MWd/kgM.

(C) CLADDING BALLOONING AND FLOW BLOCKAGE

Bases/Criteria - In the LOCA-ECCS analyses of CESSAR plants, empirical models are used to predict the degree of cladding circumferential strain and assembly flow blockage at the time of hot-rod and hot-assembly burst. These models are each expressed as functions of differential pressure across the cladding wall. There are no specific design limits associated with ballooning and blockage, and the ballooning and blockage models are integral portions of the ECCS evaluation model. PNL concludes that C-E adequately addresses this issue in their LOCA-ECCS analyses (Reference 43).

Evaluation - The cladding ballooning and flow blockage models used in the C-E LOCA-ECCS analysis described in Reference 43 are directly coupled to the models for cladding rupture temperature and burst strain [discussed in Section 3.0(C)]. The C-E cladding deformation, rupture, and flow blockage models used in Reference 43 are the same as those proposed by NRC in NUREG-0630 (Reference 46). PNL concludes that these models are not affected by the burnup extension requested in this submittal and, therefore, Reference 43 remains acceptable for application to the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

The steady-state operational input that is provided to the LOCA analysis from the FATES3B fuel performance code (Reference 20) is burnup dependent. As noted earlier [see Section 4.0(G)], the FATES3B code has been verified against data to rod-average burnups of 62 MWd/kgM and previously approved for extended burnup application to the LOCA analysis up to a rod-average burnup of 60 MWd/kgM (Reference 21). Therefore, PNL concludes that this code is also acceptable for use in providing input to LOCA analyses of the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

(D) STRUCTURAL DAMAGE FROM EXTERNAL FORCES

Bases/Criteria - To withstand the mechanical loads of a LOCA or an earthquake, the fuel assembly is designed to satisfy the stress criteria listed in Table 9-1 of Reference 44, and guide-tube deformation is limited such as to not prevent CEA insertion during the safe shutdown earthquake (SSE). These criteria have been found acceptable (Reference 15) for current burnup fuel and PNL concludes that they are acceptable for C-E 16x16 fuel designs up to a rod-average burnup of 60 MWd/kgM.

Evaluation - The C-E methods used to evaluate the mechanical loads due to a combined seismic-LOCA event are described in Reference 44. It is noted that the seismic-LOCA analyses are not affected by an increase in rod-average burnup up to 60 MWd/kgM and, therefore, previous bounding seismic-LOCA analyses remain applicable at this burnup level. This report has been approved by the NRC for current burnup levels and PNL concludes that it remains applicable for the C-E 16x16 fuel design up to a rod-average burnup of 60 MWd/kgM.

6.0 CONCLUSIONS

PNL has reviewed St. Lucie Unit 2/C-E's request, as submitted in Reference 1, to extend the burnup level of the C-E 16x16 fuel design to a rod-average burnup of 60 MWd/kgM in accordance with the SRP, Section 4.2. PNL concludes that this request by St. Lucie Unit 2 as described in Reference 1 is acceptable for licensing applications of the C-E 16x16 fuel design up to a rod-average burnup level of 60 MWd/kgM. However, PNL recommends that future requests to extend the rod-average burnup limit beyond 60 MWd/kgM should be accompanied with corrosion, cladding strain, and yield and fracture strength data at the extended burnup levels requested. These data are necessary to support the irradiation of higher burnup fuel beyond 60 MWd/kgM.

7.0 REFERENCES

1. Combustion Engineering, Inc. November 1989. Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWd/kg for Combustion Engineering 16x16 PWR Fuel for St. Lucie Unit 2. CEN-396-P, Combustion Engineering, Inc., Windsor, Connecticut.

2. Combustion Engineering, Inc. June 1989. Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWd/kgM for Combustion Engineering 16x16 PWR Fuel. CEN-386-P, Combustion Engineering, Inc., Windsor, Connecticut.

3. Letter from S. R. Petersen (U.S. Nuclear Regulatory Commission) to N. Carns (Arkansas Nuclear One) regarding "Safety Evaluation by the Office of NRR Related to Amendment Number 111 to Facility Operating License Number NPF-6," dated November 27, 1990.

4. U.S. Nuclear Regulatory Commission. July 1981. "Section 4.2, Fuel System Design." In 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.

5. 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.

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

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