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ZIRLO^{TM} Cladding and Boron Coating Models for
TXU Electric's Loss of Coolant Accident Analysis Methodologies
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TXU

ZIRLO^{TM}CLADDING AND BORON COATING MODELS FOR TXU ELECTRIC'S LOSS OF COOLANT ACCIDENT ANALYSIS METHODOLOGIES

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REACTOR ENGINEERING

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ABSTRACT

This report is presented to demonstrate the implementation of ZIRLO™ cladding and boron fuel coating models into both TXU Electric's Large and Small Break Loss-of-Coolant Accident (LOCA) Emergency Core Cooling System (ECCS) Evaluation Models. The ZIRLO™ cladding and boron fuel coating models implemented into TXU Electric's Large and Small Break LOCA methodologies are based on information supplied by the fuel vendor and are similar to the models incorporated into their Evaluation Models to account for these fuel features.

The TXU Electric Evaluation Model changes to simulate ZIRLO™ cladding and boron fuel coating during LOCAs are considered minor for two reasons: First, for ZIRLO™ , these changes are the implementation of material properties models and/or the confirmation of the applicability of existing Zircaloy models of these properties, all of which are essentially input to the analyses. For the boron fuel coating, the change is a correction to the initial pre-LOCA number of fuel rod gas moles to account for coating burn off. Second, their effect on peak cladding temperature for Comanche Peak Steam Electric Station is not significant; for example, it is much less than 50^0F in all sample cases examined. Furthermore, the implementation of these changes does not invalidate any element of the previously approved TXU methodologies. It is important to note that the subject of this report is the changes to the methodologies. It is the changes in the methodologies that are considered to be minor. Obviously, when the methodologies are applied (with or without the changes) to different fuel designs in the context of multiple core reload designs, the results may be more substantially different.

Justification is provided for the material property models deemed to adequately represent ZIRLO™ properties. The justification includes a literature search comparing property models and data of major fuel vendors, MATPRO-11 models and data, and existing and proposed TXU models. It also includes, as appropriate, discussions of the impact of some of the properties on the LOCA transient progression and sensitivity studies evaluating, in the specific context of TXU Electric's LOCA methodology, the impact of any change on the LOCA figures of merit.

In order to demonstrate the cumulative effect of the changes, several LOCA analysis figures of merit are compared for: (a) ZIRLO™ versus Zircaloy-4 cladding models, (b) separate effect of the boron coating correction, (c) combined effect of ZIRLO™ cladding models and the boron correction. (Future Comanche Peak Steam Electric Station cores are likely to have both features.) The overall impact on the representative LBLOCA results were shown to be very small. A small break LOCA case showing the combined effect of both features supports a similar conclusion.

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CHAPTER 1

INTRODUCTION

TXU Electric is currently performing the large and small break Loss-of-Coolant Accident (LOCA) Emergency Core Cooling Systems (ECCS) licensing analysis to support the operation of Comanche Peak Steam Electric Station (CPSES) Unit 1 and Unit 2. TXU Electric's Evaluation Models (References 1 and 5) are based on Framatome ANP, Inc.'s (Framatome, formerly Siemens Power Corporation) methodologies (References 2 and 6). The methodologies have been approved by the USNRC to perform the large and small break LOCA ECCS licensing analyses in compliance with USNRC regulations contained in 10 CFR 50.46 and 10 CFR 50 Appendix K.

The objective of this report is to obtain USNRC approval of changes to TXU Electric's ECCS Evaluation Models (References 1 and 5) so they may be used to analyze fuel with ZIRLO™ cladding and/or with the fuel pellets coated with boron. These features of Westinghouse Electric Corporation fuel products may be present in future fuel assemblies for CPSES, and therefore need to be incorporated into TXU Electric's large and small break LOCA ECCS Evaluation Models.

The changes to the TXU Electric LOCA methodology presented herein — including all codes, results, input decks, inferences and conclusions presented within this report — will be incorporated into TXU Electric's LOCA methodologies used to perform large and small break LOCA analyses and evaluations in compliance with 10 CFR 50.46 criteria and 10 CFR 50,

Appendix K requirements, for fuel cycle analyses and to address pertinent licensing issues for CPSES 1 and 2.

This report justifies and demonstrates the implementation of ZIRLO™ cladding and boron fuel coating models into TXU Electric's LOCA ECCS Evaluations Models. The changes made to implement ZIRLO™ cladding and boron fuel coating into TXU Electric's LOCA methodologies are similar to the changes made by the fuel vendors (Westinghouse Electric Corporation (Reference 3) and Combustion Engineering (CE) (Reference 4)).

The TXU Electric Evaluation Model changes to simulate ZIRLO™ cladding and boron fuel coating during LOCAs are considered minor for two reasons: First, for ZIRLO™, these changes are the implementation of material properties models and/or the confirmation of the applicability of existing Zircaloy models of these properties, all of which are essentially inputs to the analyses. For the boron fuel coating, the change is a correction to the initial pre-LOCA number of fuel rod gas moles to account for coating burn off. This change is merely a change in initial conditions that only impacts end of life results which have never been limiting for CPSES (e.g., References 1 and 5). Second, their effect on peak cladding temperature for Comanche Peak Steam Electric Station is not significant; for example, it is much less than 50^0F in all sample cases examined.

Furthermore, the implementation of these changes does not invalidate any element of the previously approved TXU methodologies. It is important to note that the subject of this report is the changes to the methodologies. It is the changes in the methodologies that are considered to be minor. Obviously, when the methodologies are applied (with or without the changes) to different fuel designs in the context of multiple core reload designs, the results may be more substantially different. For example, the LOCA response of a Westinghouse Integral Burnable Fuel Absorber (IFBA) fuel design with ZIRLO™ cladding might be substantially different from that of a Framatome assembly or even other Westinghouse fuels currently in the CPSES cores. These specific responses are evaluated on a reload specific basis and are beyond the scope of this report, which deals only with methodology changes.

The ZIRLO™ implementation is presented in Chapter 2. All the relevant cladding-related properties and correlations in the TXU Electric LOCA Evaluation Models are compared to Westinghouse and/or CE models, MATPRO-11 (Reference 11) models and/or data, and to Westinghouse data, whenever possible. The TXU models are then evaluated, one by one, in the context of this extensive model and data background and in the context of expected and actual impact on the TXU LOCA analysis to determine if a new model is required or whether the current Zircaloy-4 model is adequate. Whenever a new model is required, its implementation in each of the relevant LOCA codes is described.

In cases where the Zircaloy-4 property models are deemed to adequately represent ZIRLO™ properties, the following approach is used to demonstrate applicability:

(1) A context-setting literature search is made comparing property models and data of major fuel vendors to MATPRO-11 (Reference 11) models and data to existing and proposed TXU models.

(2) The conclusions and the supporting information of the vendors, who best understand the material properties of their products, are reviewed. The supporting information may take the form of material property data throughout the range of interest. In other cases, it may be based on the vendor's engineering analysis. The analysis is typically based on the existing data, the vendor's knowledge of the materials, fundamentals of materials science, and the vendor's LOCA analysis or evaluation, showing the negligible impacts of potential differences on the LOCA calculation.

(3) The importance of the property model in the context of TXU Electric's LOCA methodologies is discussed. The objective is to assess whether any potential differences in the models used for that property have a significant impact on the LOCA figures of merit[1].

(4) Sensitivity studies demonstrating the lack of sensitivity of each property model, in the specific context of TXU Electric's LOCA methodology, are performed. These sensitivity studies are done whenever there might be a choice in correlation or value to use in each of TXU Electric LOCA methodology codes.

The boron coating implementation in the TXU LOCA models is presented in Chapter 3. The thin boron coating [ ]^{a,c} on the fuel pellet surface is a burnable poison. This product is known as Integral Burnable Fuel Absorber (IFBA). The only impact of the thin boron coating

[1] In the sensitivities discussions, only peak clad temperature(PCT)is used. PCT is representative of all LOCA figures of merit in these cases, because PCT is the acceptance criterion that varies the most and these PCT variations are very small. In the analyses of Chapter 4 all LOCA acceptance criteria are presented.

on the LOCA analysis methodology is that it affects the initial pre-LOCA gas content of the fuel rod due to the helium generated as the coating becomes depleted with burnup. Therefore, only the RODEX2 code, which calculates the pre-LOCA fuel rod conditions, for both the SBLOCA and the LBLOCA, is potentially impacted.

The results of several analyses are presented in Chapter 4 to assess the cumulative effect of the changes in the individual codes. These analyses also demonstrate the implementation of the changes and present key comparisons such as: (a) The results of implementing the ZIRLO™ cladding models are compared to a case where the Zircaloy-4 models are used. No correction for the boron coating is made in either case. Two cases are performed, one at end of life and another at beginning of life. These cases show the combined effect of all ZIRLO™ cladding models when used with the TXU Electric LBLOCA methodology. (b) The results of implementing the boron coating correction are compared to an identical case except that the boron coating is not accounted for. Both cases use the ZIRLO™ cladding models. This case shows the effect of the correction within the framework of the TXU Electric methodology. (c) The results of implementing both the ZIRLO™ cladding models and the boron correction are compared to an identical case except that the Zircaloy-4 models are used and the boron coating is not modeled. This case shows the combined effect of implementing both the ZIRLO™ cladding models and the boron correction.

Finally, two SBLOCA analyses are presented to demonstrate the effect of the relevant model changes in that methodology. These cases also show that the combined effect of both features is small, leading to a conclusion similar to that reached for the large break cases.

CHAPTER 2

ZIRLO^{TM} CLADDING MODELS FOR LOCA

2.1 INTRODUCTION

This section describes the implementation of models representing ZIRLO^{TM} cladding in the USNRC-approved TXU Electric Large Break Loss-of-Coolant Accident (LBLOCA) and Small Break Loss-of-Coolant Accident (SBLOCA) Emergency Core Cooling Systems (ECCS) performance evaluation models, References 1 and 5, respectively. Section 2.2 lists the cladding material-related models for Zircaloy-4 used in both LBLOCA and SBLOCA methodologies. Section 2.3 describes the modifications that have been made to those models to represent ZIRLO^{TM} cladding. It includes a description of the cladding model for ZIRLO^{TM} for each parameter that requires a different model than Zircaloy-4. It also identifies those material-related parameters for which the Zircaloy-4 model is applicable and provides a basis for the applicability, including sensitivity studies when warranted.

The implementation of ZIRLO^{TM} cladding in the TXU Electric LOCA Evaluation Models is analogous to the USNRC-accepted implementation in the Westinghouse (and Combustion Engineering) Appendix K Evaluation Models. As described in Reference 3, Westinghouse determined that many of the physical and mechanical properties of ZIRLO^{TM} are similar to those of Zircaloy-4 when the two are in the same metallurgical phase. Consequently, many of the material property models for Zircaloy-4 are applicable to ZIRLO^{TM}. However, the change from the alpha-to-the beta phase occurs over a different temperature range in the two materials. This difference requires that a few of the Zircaloy-4 material property models be modified to more appropriately represent ZIRLO™. Specifically, the models for specific heat, cladding creep, cladding rupture temperature and strain, and assembly blockage following rupture were modified to represent ZIRLO™ in the Appendix K evaluation models.

[

]a,c

Lastly, it is noted that 10 CFR 50.46, which identifies the ECCS acceptance criteria, has been revised to extend the applicability of the criteria to fuel that is clad with ZIRLO™ cladding. Consequently, no exemptions to 10 CFR 50.46 or Appendix K thereto are needed to apply the criteria to the new analyses.

2.2 CLADDING MATERIAL-RELATED MODELS IN THE TXU ELECTRIC LOCA METHODOLOGIES

The current NRC-approved TXU Electric ECCS performance evaluation models are TXU's version of Framatome ANP, Inc.'s (Framatome) SEM/PWR-98 (References 1 and 2) for LBLOCA and TXU's version of Framatome's EXEM PWR Small Break Model (References 5 and 6) for SBLOCA.

The LBLOCA methodology is shown schematically in Figure 2.1 and includes the following computer codes: RODEX2 is used to compute initial fuel conditions such as dimensions for gap, crack and plenum volumes, gas inventory and initial stored energy. RELAP4 is used to perform the thermal-hydraulic analysis of the blowdown. RFPAC is used to perform the thermal-hydraulic analysis of the refill and reflood. Finally, TOODEE2 is used to compute the hot rod heat-up, peak clad temperature and cladding oxidation.

The SBLOCA methodology is shown schematically in Figure 2.2 and also includes the use RODEX2 and TOODEE2. The thermal-hydraulic system analysis is performed with ANF-RELAP.

The following sections will show that only a few TOODEE2 and RODEX2 models required changes to conservatively represent ZIRLO™ cladding in LBLOCA and SBLOCA analyses with respect to the acceptance criteria of 10 CFR 50.46. In addition, a few input parameters required changes in ANF-RELAP, RFPAC and RELAP4.

The list of models potentially affected by the use of ZIRLO™ cladding in LBLOCA and SBLOCA analyses is:

1. Thermal-physical properties:

    specific heat,

    density,

    thermal conductivity.

2. Thermal-mechanical properties. These are properties used in the calculation of gap conductance and of cladding diameter. These properties are:

   thermal expansion,

   modulus of elasticity,

   Poisson's ratio,

   thermal emissivity.

3. Cladding rupture, swelling and blockage models, including pre-rupture plastic strain.

4. Metal-water reaction model.

5. Cladding creep model.

2.3 IMPLEMENTATION OF ZIRLO™ PROPERTIES AND CORRELATIONS IN THE TXU ELECTRIC LOCA METHODOLOGIES

ZIRLO™ represents a modification of Zircaloy-4 reducing tin and iron content, eliminating chromium, eliminating iron and chromium precipitates and adding 1% niobium. ZIRLO™ undergoes alpha-to-beta phase changes at lower temperatures than Zircaloy-4 (Appendix A of Reference 3). Per Appendix A of Reference 3, ZIRLO™ starts the alpha-to-beta phase change at ~750^{0}C and ends at ~940^{0}C; Zircaloy-4 starts alpha-to-beta phase change at ~815^{0}C and ends at ~970^{0}C.

Since both ZIRLO™ and Zircaloy-4 are 98% Zirconium, the material properties are not significantly different except to the extent that they are affected by the phase change (Appendix

A of Reference 3). The vendor information in the following section can be found in: Section 5.2, Appendix G, and Appendix A, all of Reference 3, as well as, in Sections 6.3.2, 6.3.3 and 6.3.5 of Reference 4.

2.3.1 SPECIFIC HEAT (VOLUMETRIC HEAT CAPACITY)

The specific heat of ZIRLO^{TM} and Zircaloy-4 are virtually identical up to 750^{0}C (Figure A-3 of Appendix A of Reference 3), where the alpha-to-beta phase transformation begins for ZIRLO^{TM}. The model of the volumetric heat capacity curve for Zircaloy-4 developed by Westinghouse is shown in Figure 2.3 along with a model based on data from MATPRO-11 (Reference 11, Figures B-1.2 and B-1.3). The latter model is very similar to what is used in the various TXU Electric LOCA codes. Similar to their Zircaloy-4 model, Westinghouse developed their ZIRLO^{TM} heat capacity curve by distributing the heat of transformation over the alpha-to-beta phase change (represented by the area under the curve in Figure 2.4) between the Zircaloy-4 transition temperatures of 1093 K to 1248 K (820^{0}C to 975^{0}C) over the ZIRLO^{TM} transformation range of 1023 K to 1213 K (750^{0}C to 940^{0}C). Thus, the Westinghouse ZIRLO^{TM} heat capacity model, derived from the Zircaloy-4 data, would rise in the alpha-to-beta phase change range of 750^{0}C to 940^{0}C (instead of 820^{0}C to 975^{0}C) and would go to [ ]^{a,b,c} (see page 59 of Appendix A of Reference 3 and Figures 2.3 and 2.4).

TXU considers this approach to be theoretically sound and consistent with the physics of this property as implied in Reference 11. Therefore, the same approach is used to develop

ZIRLO™ volumetric heat capacities for the TXU codes, which is shown in Figure 2.4. It also should be noted that the TXU heat capacity model is similar to that used by CE (Reference 4, Figure 6.3.1-1) since they are based on the same Zircaloy data (Reference 11) and transformation approach. Based on the foregoing, no sensitivity studies were deemed necessary on heat capacities. The purpose of sensitivity studies is to determine the impact of material property model options on LOCA analysis figures of merit in order to derive guidance for a model choice. However, the case for the proposed heat capacity model is sufficiently compelling that no additional sensitivity runs were judged necessary[2].

In any case, LOCA analysis results are not sensitive to small changes in the heat capacity for the following reason. The heat transfer from the pellet to the coolant during a LOCA is determined by the thermal resistances of the fuel pellet, the pellet to cladding gap, the cladding, and the cladding to coolant interface, as well as the energy storage rate in the cladding. The cladding heat capacity determines the latter, which is a small term in comparison with the others because of the relatively small mass of the clad with respect to its surface area. Furthermore, differences in cladding heat capacity may have an impact on the LOCA transient in general, and cladding temperature in particular, only if the thermal resistance of the cladding is limiting the heat transfer and even then, only if the cladding heat capacity were to significantly affect the resistance of the cladding, which it does not, due to the low volume to area ratio. In none of the phases of the LOCA is the thermal resistance of the cladding limiting, nor is the energy storage in the cladding significant. The rate of heat transfer from

[2] Nevertheless, one calculation that was performed showed a PCT variation of less than 2^0F using the Westinghouse ZIRLO™ model in RELAP4 versus the TXU ZIRLO™ model, both shown in Figure 2.4.

the pellet to the coolant is dominated in the early stages by the fuel pellet resistance and in the reflood stage by the high clad to coolant heat transfer resistance.

2.3.1.1 Implementation of The ZIRLO™ Model in TOODEE2

As previously described, the TXU model does not use a step function, but rather a ramp function (based on MATPRO-11, Reference 11, similar to CE, e.g., Figure 6.3.1-1 of Reference 4) in the alpha-to-beta phase change range. Still, the same approach can be applied to derive a ZIRLO™ heat capacity for use in TOODEE2 that is analogous to the existing Zircaloy-4 data in shape and format and yet adjusted to ZIRLO™ ; i.e., distributing the heat of transformation from over alpha-to-beta phase change. Based on the above then, only three changes need to be made to obtain a TXU TOODEE2 ZIRLO™ model, from the Framatome data table of page 11-4 of Reference 8:

The first change is to switch the alpha-to-beta phase change initiation temperature from [ ]a,b,c and the end transition temperature from [ ]a,b,c

The second step is to adjust the peak value of the heat capacity (85.176 BTU/ft^3 ^{0}F) such that the area under the curve remains the same, as described on page 59 of Appendix A of Reference 3. The adjustment here is made based on the Westinghouse transition temperature interval ratio from alpha-to-beta phase, [

]a,b,c

[

]a,b,c

The ZIRLO™ heat capacity model to be inserted into TOODEE2 is shown in Table 2.1.

2.3.1.2 Implementation of The ZIRLO™ Model in RELAP4, RFPAC and ANF-RELAP

These codes are used to provide the thermal-hydraulic boundary conditions for the fuel rod heat-up calculations performed with TOODEE2: RFPAC and RELAP4, for LBLOCA and ANF-RELAP for SBLOCA. The heat capacity of the cladding can be provided as input in RFPAC and RELAP4 so that no code modifications are needed and the values to be used as input for ZIRLO™ are those presented in Table 2.1. RFPAC also uses the same tabular values, except that they are read from within the source code so that a code change is required, albeit trivial.

2.3.1.3 RODEX2

This code is used to compute the initial conditions in the fuel rod prior to the LOCA. Therefore, although conservatism is included, these are all normal operating conditions prior to the accident. As a result, cladding temperatures are in the 550°F to 750°F range, which is significantly less than the onset of the ZIRLO™ phase change at 1382°F (750°C). Thus, both cladding materials are always in the alpha phase for the range of conditions examined with this code. As shown in Figure A-3 of Appendix A of Reference 3, the heat capacities of Zircaloy-4 and ZIRLO™ are virtually identical in the alpha phase and no changes to the code or the input models are required for RODEX2. The existing model is an adequate representation for ZIRLO™ in the temperature range where the code is used.

2.3.2 DENSITY

Cladding density is not used explicitly in the TXU Electric LOCA methodologies. Density is only used to convert MATPRO-11 (Reference 11) specific heat data to volumetric heat capacity for use in the RFPAC and RELAP4 codes. Since only the volumetric heat capacity is actually used in the TXU codes (see Section 2.3.1 for that model), there is no need to modify density values. Although not relevant to TXU methodologies, it may be of interest to note that differences in density are only around 2% (6.425 gm/cc for ZIRLO™ versus 6.578 gm/cc for Zircaloy-4, per Reference 3 page 58), and would be less (~1%) in the context of RFPAC and RELAP4, since those codes use a value of 6.5 to convert Zircaloy-4 specific heat to volumetric heat capacity.

2.3.3 THERMAL CONDUCTIVITY

As described in Section 2.3.1, the heat transfer from the pellet to the coolant during a LOCA is determined by the thermal resistances of the fuel pellet, the pellet to cladding gap, the cladding, and the cladding to coolant interface. Differences in cladding thermal conductivity may have an impact on the LOCA transient in general, and cladding temperature in particular, only if the thermal resistance of the cladding is limiting the heat transfer. CE (Reference 12) has provided an excellent demonstration that this is not the case. In none of the phases of the LOCA is the thermal resistance of the cladding limiting. The rate of heat transfer from the pellet to the coolant is dominated in the early stages by the fuel pellet resistance and in the reflood stage by the high clad to coolant heat transfer resistance. The lack of sensitivity seen in the sensitivity studies performed by TXU and the discussion of the following sections confirms this analysis.

2.3.3.1 <u>RODEX2</u>

Figure 2.5 shows a comparison of various models and data for the thermal conductivity. These are: (1) Westinghouse Appendix K correlation (same for ZIRLO™ and Zircaloy-4), (2) CE correlation (same for ZIRLO™ and Zircaloy-4), (3) RODEX2 correlation for Zircaloy-4, (4) MATPRO-11 correlation for Zircaloy-2 and Zircaloy-4 combined, where the error bars are used to show data scatter (e.g Reference 11, Figure B.2.1), (5) Westinghouse data for Zircaloy-4 and (6) ZIRLO™. RODEX2 is used to compute the initial conditions in the fuel rod prior to the LOCA. Although conservatism is included, these are all normal operating conditions prior to the accident. Therefore, cladding temperatures are in the 550^{0}F to 750^{0}F range in RODEX2 calculations. Figure 2.5 clearly shows that except for the Westinghouse ZIRLO™ data, which is only slightly off, all other data and correlations fall within the MATPRO-11 correlation (Reference 11) data scatter band. The Westinghouse data is from Figure A-2 of Reference 3, where it is observed that the ZIRLO™ data is approximately 10% higher than the Zircaloy-4 data in the temperature range of interest. A sensitivity study was performed whereby the RODEX2 correlation was increased by 10% to fit the existing Westinghouse ZIRLO™ data better, as illustrated in Figure 2.6. The resulting variation in PCT was less than

1^0F . As a result of this lack of sensitivity, and given the close comparisons between the various models presented in Figure 2.5, the existing RODEX2 correlation is deemed an adequate representation for ZIRLO™ thermal conductivity.

2.3.3.2 RELAP4, RFPAC, ANF-RELAP, TOODEE2

Figure 2.7 compares the models used in these codes to the MATPRO-11 (Reference 11, Equation B-2.3 and Figure B-2.1). The figure also shows Westinghouse and CE models (both apply to Zircaloy-4 as well as to ZIRLO™). Figure 2.7 clearly shows that all models are within the error band around the MATPRO-11 correlation in the range of interest ($T< 2200^0F$). Although the Westinghouse ZIRLO™ data from Figure A-2 in Reference 3 is limited to $T< 1300^0F$, it is nearly within the error band in the MATPRO-11 correlation, as can be seen in Figure 2.5. Nevertheless, this limited data seem to indicate that ZIRLO™ thermal conductivity might be ~10% higher than that of Zircaloy-4, and trending towards the Zircaloy-4 data at higher temperatures. In order to investigate the effect of ZIRLO™ thermal conductivity being ~10% higher, the existing models in the TXU codes were increased by 10%. The PCT variations resulting from using 110% of the model in each code were not significant (RELAP4 $\Delta PCT< 3^0F$, TOODEE2 $\Delta PCT< 1^0F$, RFPAC $\Delta PCT< 1^0F$). The ANF-RELAP $\Delta PCT< 7^0F$ was for a 20% range of thermal conductivity varying between 90% and 110% of the existing Zircaloy-4 thermal conductivity model shown in Figure 2.7.

Thus, it is judged appropriate to use the existing models to represent ZIRLO™ thermal conductivity in the TXU LOCA codes. The basis for this is: (a) ZIRLO™ data is very nearly within the data spread around the MATPRO-11 correlation used for Zircaloy-4 in the TXU codes, (b) based on the data trend seen in Figure A-2 of Reference 3 and Figure 2.6, the ZIRLO™ data appears to be trending towards that of Zircaloy-4 at temperatures above 1300^{0}F, which are more relevant to the phases of the LOCA analysed with these codes, (c) because the thermal resistance of the clad never restricts the heat transfer from the pellet to the coolant (d) an increase of 10% in the thermal conductivity models has virtually no impact on LOCA figures of merit and (e) because both the Westinghouse and the CE ZIRLO™ models (same as Zircaloy-4) provide nearly identical values of thermal conductivity to the proposed TXU ZIRLO™ model (same as Zircaloy-4), as shown in Figure 2.7.

2.3.4 THERMAL EXPANSION

The thermal expansion or contraction of the cladding affects the calculation of the change in cladding inside diameter. This change, together with the change due to plastic strain (and to a very small extent the change due to mechanical expansion or contraction in the elastic regime) is used to calculate gap conductance, the total gas volume and thus the rod internal pressure. The component of the change in cladding diameter due to thermal expansion is small in comparison to the change due to plastic strain, as the clad approaches its burst temperature. Therefore, at higher temperatures where the differences between the various thermal expansion models reviewed here are greater (and where data uncertainty and standard deviation are greater), the plastic strain dominates the change in clad inside diameter. For example, at ~1600^{0}F it would only take ~190 psi rod-to-coolant pressure differential for there to be significant plastic strain. At lower temperatures, where the plastic strain is small or nonexistent, there is little difference between the various thermal expansion models as shall be seen in the following sections, thus, the lack of LOCA sensitivity to variations this parameter within the range of the existing and proposed models reviewed below.

2.3.4.1 RODEX2

Figure 2.8 shows a comparison of the thermal expansion models used in: (1)Westinghouse Appendix K codes (same model for ZIRLO™ and Zircaloy-4), with (2) RODEX2 correlations for Zircaloy-4 (there are two, which give identical values in the temperature range of interest), with (3) MATPRO-11 correlation for Zircaloy-2 and Zircaloy-4 combined, where the error bars are used to show data scatter (e.g Reference 11, Figure B-4.3), with (4) Westinghouse data for Zircaloy-4 and (5) ZIRLO™, the latter two from Figure A-1 in Reference 3. RODEX2 is used to compute the initial conditions in the fuel rod prior to the LOCA. Although conservatism is included, these are all normal operating conditions prior to the accident. Therefore, cladding temperatures are in the 550^0F to 750^0F range for the range of conditions examined with this code. Figure 2.8 shows that the RODEX2 correlations fall within the upper error band on the MATPRO-11 correlation (Reference 11) while the Westinghouse correlation falls near the lower range of that data scatter band. The Westinghouse data is from Figure A-1 in Reference 3, where it is observed that the ZIRLO™ data overlaps the Zircaloy-4 data in the temperature range of interest and is slightly lower than the MATPRO-11 data. Since there is a slight difference between the various correlations and data, a sensitivity run was performed wherein the Westinghouse correlation was inserted into RODEX2. The PCT difference was less than 1^0F ($\Delta PCT < 1^0F$). Since existing data in the temperature range of interest shows there is no difference between the thermal expansion of ZIRLO™ and Zircaloy-4 and given the lack of sensitivity between the existing models and the sound basis for the RODEX2 model which lies within the MATPRO-11 correlation data error band, it is judged that the existing thermal expansion model in RODEX2 is an appropriate representation of the thermal expansion of ZIRLO™ for LOCA analyses.

2.3.4.2 RELAP4, RFPAC, ANF-RELAP, TOODEE2

RFPAC is only used to provide the thermal hydraulic boundary conditions for the fuel rod heat-up analysis which is performed in TOODEE2. Thus, RFPAC only uses two of the properties potentially affected: thermal conductivity and heat capacity, which were discussed in previous sections. Thermal expansion is not used in the RFPAC calculation.

Figure 2.9 is a comparison of the models used in the remaining codes to the MATPRO-11 (Reference 11, Figure B-4.3) model. A Westinghouse model, which applies to Zircaloy-4 as well as to ZIRLO™ and is also used by CE for both materials (Reference 4) is also shown. Figure 2.9 clearly shows that all TXU models are within the error band around the MATPRO-11 data fit, which is 10% for $T<\sim1400^0F$ and 50% for $T>\sim1400^0F$.

RELAP4 values above $\sim1400^0F$ are not relevant because the code is only used in the blowdown phase of the LOCA and in CPSES applications, the blowdown phase clad temperatures are always well below 1400^0F (e.g. Figure 3.15 in Reference 1). A sensitivity run was performed by installing the MATPRO-11 model, also used in ANF-RELAP into RELAP4. However, as expected, there was no effect on PCT. As a practical matter, though, due to the lack of pedigree of the current thermal expansion input into RELAP4, it is proposed that the

MATPRO-11 model also used in ANF-RELAP be input into RELAP. This model is applicable to ZIRLO™ as well as to Zircaloy, as explained below. These changes are implemented via input data cards and no code changes are required.

The MATPRO-11 correlation is used the TXU SBLOCA code ANF-RELAP. The change in slope in this correlation and in its supporting data is due to change from alpha-to-beta phase. Since it is shown in Figure A-1 of Reference 3 that the thermal expansion of ZIRLO™ and Zircaloy overlap when materials are in the alpha phase it is reasonable to assume they are also very similar in the beta phase. Therefore, it would be a simple matter to modify this correlation to account for the difference in phase change temperatures for these materials. However, given the large uncertainty in the data in the phase transition range and in the beta phase (50%), and as a result of a lack of sensitivity to this parameter, such an adjustment is not justified. For example, it can be seen in Figure 2.9 that Westinghouse does not even account for the phase change at all in its models. In addition, sensitivity studies on CE models (Reference 4), which are also similar to the MATPRO-11 model (Figure 6.3.5-1 of Reference 4) also resulted in negligible impact on LOCA figures of merit when the correlation slope change range was modified to the ZIRLO™ phase change temperatures. In the case of the model in TOODEE2, where the phase change is also accounted for, as also shown in Figure 2.9, a sensitivity study similar to that conducted by CE showed that when the model is modified to account for the difference in the phase change temperatures the variation in peak clad temperature is negligible (ΔPCT< 2^0F).

Therefore, given the lack of sensitivity of LOCA figures of merit to relatively small changes in the thermal expansion due to differences in the phase change temperatures, given that all TXU models are within the MATPRO-11 uncertainty band in their range of applicability (note the 50% band in the Zircaloy thermal expansion data above ~1400^{0}F), and given the ZIRLO™ and Zircaloy alpha phase thermal expansion overlap, it is appropriate to use the existing thermal expansion models to represent ZIRLO™ in TOODEE2 and ANF-RELAP.

2.3.5 MODULUS OF ELASTICITY

The modulus of elasticity works together with Poisson's ratio. The theoretical explanation for the lack of impact of these properties on LOCA figures of merit, as shall be evident in the following sections, is given in Section 2.3.6.

2.3.5.1 RODEX2

Figure 2.10 shows a comparison of the modulus of elasticity models used in: (1) Westinghouse Appendix K codes (same for ZIRLO™ and Zircaloy-4), with (2) the RODEX2 models for Zircaloy-4, with (3) the CELMOD model used in RELAP4 and TOODEE2 and favorably evaluated in the MATPRO-11 document (Reference 11), where the error bars are used to show the standard error of 10% (e.g., Reference 11, Section 5.5), with (4) a CE model discussed in Reference 4. RODEX2 computes the initial conditions in the fuel rod prior to the LOCA. Although conservatism is included, these are all normal operating conditions prior to the accident. Therefore, cladding temperatures are in the 550^{0}F to 750^{0}F range in RODEX2 calculations. Figure 2.10 shows that the RODEX2 and Westinghouse correlations are well within the standard error of CELMOD which is essentially validated in MATPRO-11. The CE correlation is the most different, although in the range of interest it is nearly within the standard error bands as well. As a precaution, a sensitivity run was performed where the CE correlation was inserted into RODEX2. The difference in peak clad temperature was negligible ($\Delta PCT < 1^0F$).

Thus, given that: (1) there is essentially no sensitivity between the various models for purposes of LOCA analysis; (2)the basis for the existing RODEX2 model is sound and that it falls within the standard error of CELMOD (MATPRO-11, Reference 11); (3) the RODEX2 model is nearly identical to the Westinghouse ZIRLO™ model (Figure 2.10) and ; (4) Westinghouse has concluded that the elastic modulus of ZIRLO™ and Zircaloy-4 are essentially identical (Reference 12, RAI 6b and RAI 7, page 14 of 67), it is concluded that the existing RODEX2 model shown in Figure 2.10 adequately represents the elastic modulus of ZIRLO™ in the range of expected use.

2.3.5.2 RELAP4, RFPAC, ANF-RELAP, TOODEE2

RFPAC is only used to provide the thermal hydraulic boundary conditions for the fuel rod heat-up analysis which is performed in TOODEE2. Thus RFPAC only uses two of the properties potentially affected: thermal conductivity and heat capacity, which were discussed in previous sections. Modulus of elasticity is not used in the RFPAC calculation.

Figure 2.11 shows a comparison of the remaining TXU models (RELAP4, TOODEE2, ANF-RELAP), which use the CELMOD program of MATPRO-11 (Reference 11) with the

Westinghouse and CE models. Since there is some difference between the models, with the most different being the CE model, various sensitivity runs were performed in which the CE model was substituted in the TXU codes. The sensitivities were: RELAP4 $\Delta PCT < 1^0F$, TOODEE2 $\Delta PCT < 1^0F$, ANF-RELAP $\Delta PCT < 1^0F$.

Thus, given that: (1) there is essentially no sensitivity between the various models for purposes of LOCA analysis; (2)the existing TXU model basis for modulus of elasticity in RELAP4, TOODEE2, ANF-RELAP is the CELMOD program (MATPRO-11, Reference 11); and (3) Westinghouse has concluded that the elastic modulus of ZIRLO™ and Zircaloy-4 are essentially identical (Reference 12, RAI 6b and RAI 7, page 14 of 67), it is concluded that the existing RELAP4, TOODEE2 and ANF-RELAP models shown in Figure 2.11 adequately represent the elastic modulus of ZIRLO™.

2.3.6 POISSON'S RATIO

The modulus of elasticity in conjunction with Poisson's ratio are used in the calculation of the cladding inside diameter change due to mechanical expansion or contraction of the cladding in the elastic regime. This change, together with the change due to thermal expansion and plastic strain, is used to calculate gap conductance, the total gas volume and thus the rod internal pressure. The mechanical component of the change in cladding diameter in the elastic regime is small in comparison to the change due to thermal expansion and even more so to plastic strain which occurs as the clad approaches its burst temperature, thus, the lack of LOCA sensitivity to this parameter as shall be presented in the following paragraphs.

2.3.6.1 RODEX2, RELAP4, RFPAC, ANF-RELAP, TOODEE2

RFPAC is only used to provide the thermal hydraulic boundary conditions for the fuel rod heat-up analysis which is performed in TOODEE2. Thus RFPAC only uses two of the properties potentially affected: thermal conductivity and heat capacity, which were discussed in previous sections. Poisson's ration is not used in the RFPAC calculation.

Figure 2.12 is a comparison of Poisson's ratio: (1) used in Westinghouse and CE Appendix K codes (same for ZIRLO™ and Zircaloy-4), with (2) RODEX2 for Zircaloy-4, with (3) the RELAP4 and TOODEE2 model, with (4) the ANF-RELAP model. The RODEX2 model is a constant value of 0.4 whereas the ANF-RELAP model is a constant value of 0.3. The CE and Westinghouse model is the same. It shows a slight decrease with temperature, while the RELAP4 and TOODEE2 model shows a slight increase with temperature. Overall, all models give values that range from 0.2 to slightly above 0.4. Since there are differences in the various models, sensitivity studies were performed to assess the impact of these differences in the results of LOCA analyses. For RODEX2, which uses a value of 0.4 a case was run with a value of 0.25, which would be the minimum value of all models in the temperature range of interest for this code. The result was a ΔPCT< 1^0F. Similarly, in RELAP4 and TOODEE2, the CE (Westinghouse) model was used in a sensitivity study and again the result was a ΔPCT< 1^0F for each code. In the case of ANF-RELAP, a value of 0.2 was used in the sensitivity study, because the temperature range of interest is higher than that for RODEX2, but again the result was a ΔPCT< 1^0F.

Thus, given that there is no sensitivity between the various models for purposes of LOCA analysis and that Westinghouse has concluded that Poisson's ratio of ZIRLO™ and Zircaloy-4 are essentially identical (Reference 12, RAI 6c and RAI 7, page 14 of 67), it is concluded that the existing models shown in Figure 2.12 are adequate models to represent Poisson's ratio of ZIRLO™ in RODEX2, RELAP4, TOODEE2 and ANF-RELAP.

2.3.7 THERMAL EMISSIVITY

In the case of RODEX2, the emissivity is a clad property applicable to the radiation heat transfer component of the fuel-clad gap conductance. Radiation heat transfer is not a significant contributor to the gap conductance (note the temperatures range $550^0F < T < 750^0F$) and that explains the lack of sensitivity to changes in its value as shown in Section 2.3.7.1.

In the case of RELAP4 and TOODEE2, the radiation heat transfer can take place between the hot rod and/or hot assembly and the neighboring rods and/or assemblies. It is small in comparison to other heat transfer modes and for that reason, changes in emissivity values have little impact on LOCA analysis results for these codes as shown below in Section 2.3.7.1.

2.3.7.1 <u>RODEX2, RELAP4, RFPAC, ANF-RELAP, TOODEE2</u>

RFPAC is used only to provide the thermal hydraulic boundary conditions for the fuel rod heat-up analysis which is performed in TOODEE2. Thus RFPAC only uses two of the properties potentially affected: thermal conductivity and heat capacity, which were discussed in previous sections. Thermal emissivity is not used in RFPAC calculations.

Radiation heat transfer is not credited in the thermal-hydraulic analysis portion of the SBLOCA methodology, although it is used in the rod heat-up calculation. Thus, thermal emissivity is not used in ANF-RELAP calculations.

Figure 2.13 shows a comparison of the thermal emissivity models used in: (1) CE Appendix K codes (same for ZIRLO™ and Zircaloy-4), (2) TXU codes RODEX2, RELAP4 and TOODEE2 and (3) MATPRO-11 (Reference 11, Figure B-3.3), showing the standard deviation about the model prediction. TXU codes use a constant value of 0.9 while the MATPRO-11 model is a constant value of 0.8, with a standard deviation of +/- 0.1. The CE model shows the emissivity increasing with temperature. As inferred from Reference 11, the emissivity is expected to be constant and to decrease for temperatures greater than 1573 K (2372^{0}F). Figure B-3.3 of Reference 11 shows that the emissivity is a property of the oxide layer and is not dependent on whether the cladding is in the alpha or beta phase, i.e., there are no inflections, discontinuities, etc., in the behavior of the emissivity over the transition temperature range. As stated in Reference 3, Appendix A, since ZIRLO™ and Zircaloy-4 are 98% Zirconium, their properties are insignificantly different except to the extent that they are affected by differences in the temperature range over which the alpha-to-beta phase change occurs. Consequently, it is expected that the emissivity of ZIRLO™ is also not dependent on the alpha-to-beta phase transition temperature range and therefore its emissivity would be similar to Zircaloy-4. Again, the MATPRO-11 model, in whose upper bound the TXU model is situated, is for the oxidized cladding and both materials are 98% Zirconium. Therefore, it is concluded that it is appropriate to use the existing model (constant value of 0.9) as an adequate representation of thermal emissivity of ZIRLO™ in RODEX2, RELAP4 and TOODEE2.

Recognizing that there is a difference in the values used by CE (Reference 4), sensitivity runs were performed. For RODEX2 a constant value of 0.3 was used, which corresponds to the approximate minimum value for the CE model in the clad temperature range of $550^0F < T < 750^0F$. This model resulted in a RODEX2 $\Delta PCT < 2^0F$. For RELAP4 and TOODEE2, the temperature range where radiation might even be considered a factor is $T > 1000^0F$, and the minimum emissivity value in that range in the CE model is ~0.5, which is used in sensitivity studies of these codes. The results of these sensitivity runs were: RELAP4 $\Delta PCT < 2^0F$, TOODEE2 $\Delta PCT < 1^0F$. These differences are not significant.

2.3.8 CLADDING BURST STRAIN, RUPTURE TEMPERATURE AND ASSEMBLY BLOCKAGE

NUREG-0630 (Reference 7) describes the cladding rupture temperature, rupture strain, and assembly blockage models that were developed by the NRC for use in Appendix K evaluation models. The NUREG-0630 rupture temperature, rupture strain, and assembly blockage models are used in the TXU Electric and Westinghouse Appendix K Evaluation Models for Zircaloy-4. However, because of the change in the temperature range over which the alpha-to-beta phase change occurs for ZIRLO™ versus Zircaloy-4, the models are not directly applicable to ZIRLO™ cladding. Westinghouse conducted a rod burst test program for ZIRLO™ cladding and, following the methodology of NUREG-0630, developed rupture and blockage models for ZIRLO™ cladding that are used in the Westinghouse Appendix K Evaluation Models. TXU has implemented a similar model based on the Westinghouse data.

In these models, the rupture temperature is determined as a function of the hoop stress (which correlates to the rod-to-coolant pressure differential). The models also provide the strain at burst, which is used to determine the channel blockage fraction if it occurs. In addition, a permanent (plastic) hoop strain is established in the cladding when the temperature gets within ~200 ^{0}F of the burst temperature. Thus, differences in these characteristics can potentially have a non-negligible impact on the fuel rod response to the LOCA, especially when combined with other differences in fuel design, e.g., the initial rod backfill pressure. However, from a methodology point of view, the changes are not considered to be significant, i.e., the changes in these models do not affect the already existing applicability of the methodology to compute LOCA figures of merit (although the figures of merit themselves may vary when fuel design changes are combined with the rupture model changes). Another way to make the same point is that the accident progression is similar for cases that differ only with respect to these models. The focus of this report is methodology, so potential response differences due to fuel differences are not in the scope of the report because TXU has been and will continue to perform LOCA analyses of its fuel at every reload, as needed. Nevertheless, informal application of the TXU LOCA methodology to Westinghouse fuel with ZIRLO™ cladding shows the range of possible responses is similar to that of Framatome fuel; although, the response in any given scenario may be different. Even so, there are factors that make this variation less for CPSES reload-specific applications than it might be for a once-in-a-lifetime generic plant analysis. For example, the top-skewed power shapes which are characteristic of CPSES core designs tend to cause rupture to occur (if it occurs) at or just downstream of the peak power node. When rupture occurs(or doesn't) in the cases being compared, the time of rupture and results tend to be similar. It is when rupture occurs in one case and not in another, that the accident progression (and thus the LOCA figures of merit) differs the most.

2.3.8.1 Implementation of the ZIRLO™ Model in TOODEE2

The Westinghouse burst temperature correlation is shown in Figure 5-2 of Reference 3 along with the Zircaloy-4 correlation it replaced. It should be noted that in the Westinghouse tests, ZIRLO™ showed [ ]a,b,c

Figure 2.14 is a copy of Figure 5-2 of Reference 3 showing where the Framatome model of Equation 16 of Reference 8 and the data[3] of the table on page 3-6 of Reference 8, which apply to Zircaloy, fall with respect to the Westinghouse models for Zircaloy-4 (solid lines) and ZIRLO™ (dashed line). The ZIRLO™ model for burst temperature inserted into TOODEE2 is also shown in Figure 2.14. As with the Zircalloy-4 model, this ZIRLO™ model basically uses data points above a cutoff temperature and Equation 16 of Reference 8 below that. What makes it ZIRLO™-specific is that the data points and the heat-up rate in Equation 16 of Reference 8 are chosen such that a good fit to the ZIRLO™ Westinghouse data is obtained. Specifically:

[ ]a,b,c

[ ]a,b,c

[3]The data points apply above a cutoff temperature and the equation below that cutoff temperature.

(3) The new tabular data to replace that of page 3-6 of Reference 8 was obtained as follows: The new entry point at [

]^{a,b,c} and etc. These points were then plotted and additional points developed from the resulting smoothed curve (Figure 2.11). The "new" tabular data set for ZIRLO™ is given in Table 2.2.

The burst strain table on page 3-7 of Reference 8 is also modified for ZIRLO™ according to the Westinghouse data in Figure D-8 of Reference 3 and Figure 5-3 of Reference 3. Note that the NUREG-0630 burst strains shown in Figure D-8 (Reference 3) for Zircaloy-4 correspond to those of Framatome's table on page 3-7 of Reference 8. As discussed above, Westinghouse test data showed that [ ]^{a,b,c} The data shown below and implemented in TOODEE2 corresponds to the Westinghouse ZIRLO™ strain LOCA model shown in Figure 5-3 of Reference 3.

The assembly blockage model in the Framatome TOODEE2 model is derived directly from burst strains. Therefore, no changes in this model are required as ZIRLO™ properties are already reflected in the revised burst strains.

2.3.8.2 RELAP4, RFPAC and ANF-RELAP

The following codes are used to provide the thermal-hydraulic boundary conditions for the fuel rod heat-up calculations performed by TOODEE2: RFPAC for LBLOCA and ANF-RELAP for SBLOCA. Therefore, rupture models in these codes would only be relevant for LOCA analysis if they were to affect the thermal-hydraulic boundary conditions for the hot rod. For this to occur it would be necessary that a potential for rupture exist for all the average core rods in a large break LOCA or the 20% hottest core region rods in a small break LOCA. This is never the case. In fact, there are no active rupture models in either RFPAC or ANF-RELAP. However, in the case of RELAP4 which models the blowdown phase of the LOCA not only for large regions of the core, but also for the hot assembly, it is prudent to replace the Zircaloy-4 rupture model with the ZIRLO™ rupture model, even though there has never been a blowdown phase rupture in RELAP4 in a CPSES application with the current methodology. In RELAP4, the rupture model is input as data points and therefore code changes are not needed. For ZIRLO™ applications, these input values were changed in RELAP4 so as to match the ZIRLO™ rupture data presented in this section.

2.3.8.3 RODEX2

RODEX2 is used to compute the initial conditions in the fuel rod prior to the LOCA. Although conservatism is included, these are all normal operating conditions prior to the accident. Therefore, cladding temperatures are in the 550^0F to 750^0F range in RODEX2 calculations. Therefore, this code has no rupture model.

2.3.9 METAL-WATER REACTION

Westinghouse also demonstrated that the use of the Baker-Just model for the calculation of the metal-water reaction rate, which is a required feature of Appendix K Evaluation Models, is [ ]^{a,b,c} Although Westinghouse developed a new model in order to take advantage of improved behavior for ZIRLO™, the TXU Electric Evaluation Models [ ]^{a,c}

2.3.10 CLADDING GROWTH AND CREEP

This section deals with the impact of cladding creep and axial growth on LOCA analysis only. While these effects can be very important for fuel design, that scope remains the responsibility of the fuel vendor. Fuel design considerations (e.g., fatigue, corrosion, most implications of creep and growth, etc.) are not required for ECCS Evaluation Models and therefore are not within the scope of this report.

Cladding creep and axial growth do not have a significant impact on LOCA limits for CPSES because they affect cladding dimensions over time, i.e., they affect the initial conditions for the accident but not the accident progression itself. For this reason, cladding creep and axial growth need to be addressed only for RODEX2. None of the other codes in either the small or large break LOCA methodologies include creep or axial growth models. Furthermore, cladding creep and axial growth have little or no effect on beginning of life LOCA analyses, which have historically been the most limiting for CPSES. Therefore, the cladding creep and axial growth models in RODEX2 need not be as elaborate as the vendor's fuel ZIRLO™ - specific models (e.g. PAD 4.0) which are used for fuel design applications. Thus, the cladding creep and axial growth Zircalloy-4 models in RODEX2 were changed in a manner similar to what was done by Westinghouse to model ZIRLO™ in PAD 3.4 (Reference 10) for LOCA applications.

2.3.10.1 Implementation in RODEX2

[

]^{a,c} This factor was used in PAD 3.4 to obtain quantitative predictions of other ZIRLO™ creepdown data. These quantitative comparisons verify that a ZIRLO™ total in reactor creep ratio of [

]^{a,c} A predicted to measured plot is shown as Figure B-2 of Reference 3.

[

]^{a,c}

The RODEX2 Zircaloy-4 creep rate equation is given in Reference 2 (Section 3-5.1):

$\epsilon_g = \epsilon_{g\ th\ cr} + \epsilon_{g\ irr\ cr}$

where,

{ }

and,

{ }

Both k_{th} and k_{irr} are constants. Based on the ZIRLO™ to Zircaloy-4 creep ratio discussed above, [ ]^{a,c}, it is necessary to adjust the creep rates in the RODEX2 model above as follows:

$k_{th,Zirlo} = (0.8)^{1/2} \cdot k_{th,Zircaloy}$ and,

$k_{irr,Zirlo} = 0.8 \cdot k_{irr,Zircaloy}$

Note that [ ]^{a,c} is an overall factor that applies to thermal as well as to irradiation creep (Reference 9). From Table 3.9 of Reference 2, the following constants then need to be changed in RODEX2 to represent ZIRLO™ creep rates:

$AHM(1) = \ln(A_\theta K_{th})$

$ALM(1) = \ln(A_\theta \ B_\theta^{1.23} K_{irr})$

Based on the relations developed above for the ratios $k_{th,Zirlo}/k_{th,Zircaloy}$ and $k_{irr,Zirlo}/k_{irr,Zircaloy}$:

[ ]^{a,c} and,

[ ]^{a,c}

The RODEX2 Zircaloy-4 axial growth factor is :

{ }

Based on Westinghouse's ZIRLO™ to Zircaloy-4 axial growth ratio discussed above, [ ]^{a,c}, it is necessary to adjust the constant in the RODEX2 model above as follows:

{ }

resulting in the ZIRLO™ growth model implemented in RODEX2 for LOCA applications.

Creep and growth affect cladding dimensions over time, and therefore have little or no effect on beginning of life LOCA analyses results with TXU Electric methodologies. For example, for beginning of life cases, it was found that the change in the creep model and/or the growth model in RODEX2 resulted in a $\Delta PCT < 1^0F$. Even for end of life cases, the impact of the changes described in this section on LOCA analyses with TXU Electric methodologies was small. In sensitivity studies, it was found that the change in the creep model in RODEX2 resulted in a $\Delta PCT < 5^0F$ at end of life. A $\Delta PCT < 15^0F$ impact was found for the change in the growth model and the combined change resulted in a $\Delta PCT < 10^0F$ at end of life.

2.3.10.2 RELAP4, RFPAC, TOODEE2 and ANF-RELAP

Cladding creep and axial growth only needed to be addressed for RODEX2. None of the other codes in either the small or large break LOCA methodologies has creep or axial growth models.

Table 2.1 - ZIRLO™ Heat Capacity versus Temperature

a,b,c

Table 2.2- ZIRLO™ Rupture Temperatures versus Hoop Stress

a,b,c

Table 2.3 - ZIRLO™ Rupture Temperatures versus Burst Strain

a, b, c

Figure 2.1

Schematic Representation of TXU Electric's LBLOCA Methodology

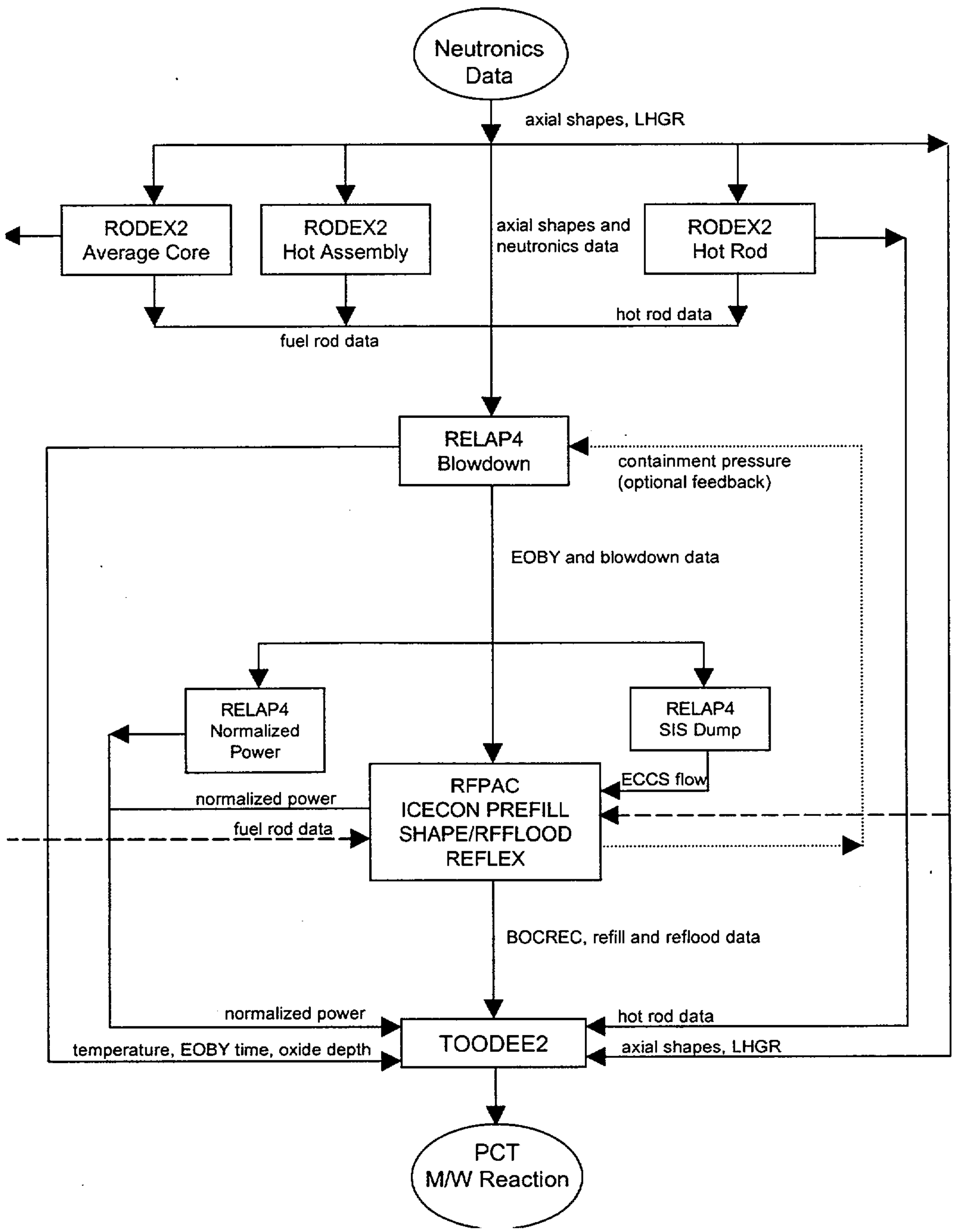
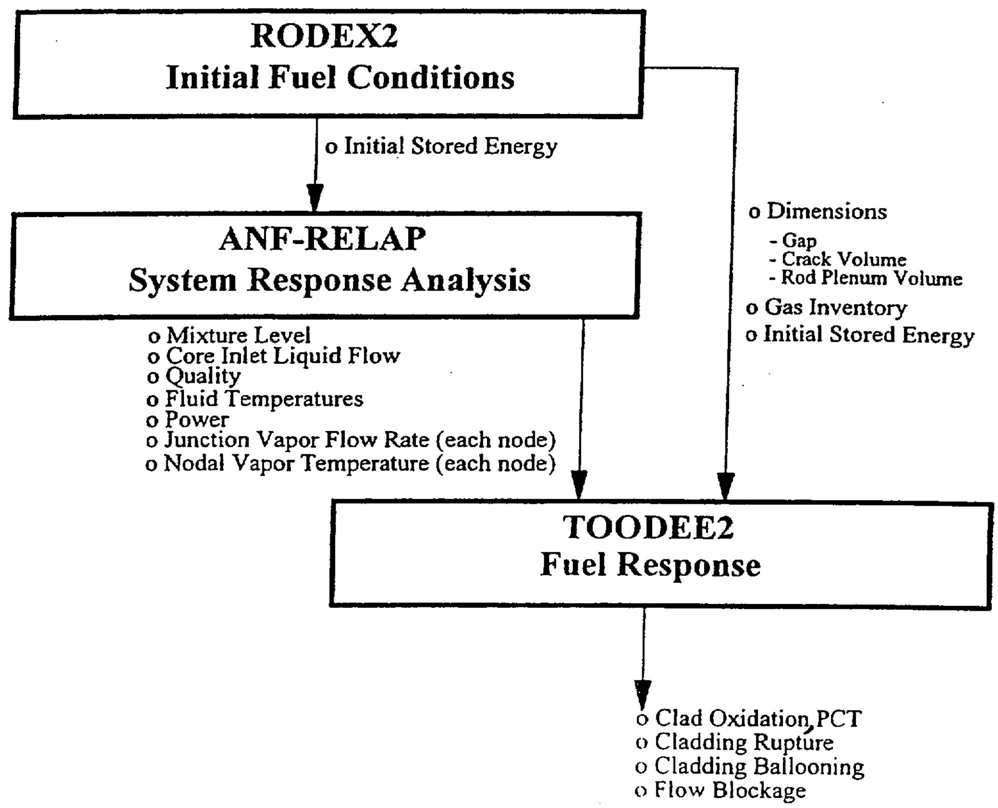


Figure 2.2

Schematic Representation of TXU Electric's SBLOCA Methodology



a,b,c

Figure 2.3

Zircaloy-4 Heat Capacity

a,b,c

Figure 2.4

ZIRLO™ Heat Capacity

a,b,c

Figure 2.5

Thermal Conductivity - 1

a,b,c

Figure 2.6

Thermal Conductivity - 2

a,b,c

Figure 2.7

Thermal Conductivity - 3

a,b,c

Figure 2.8

Thermal Expansion - 1

a, b, c

Figure 2.9

Thermal Expansion - 2

a, b, c

Figure 2.10

Modulus of Elasticity - 1

a,b,c

Figure 2.11

Modulus of Elasticity - 2

a, b, c

Figure 2.12

Poisson's Ratio

a,b,c

Figure 2.13

Clad Emissivity

a,b,c

Figure 2.14

ZIRLO^{TM} NUREG-0630 Burst Temperature Model

as Implemented in TXU Electric's Methodologies

a,b,c

Figure 2.15

ZIRLO™ Burst Temperature Model versus Hoop Stress

as Implemented in TXU Electric's Methodologies

CHAPTER 3

BORON COATING IMPLEMENTATION

3.1 INTRODUCTION

One of the fuel features under consideration for future cycles at Comanche Peak Steam Electric Station Units 1 and 2 is a thin [ ]a,c boron coating on the fuel pellet surface. The resulting product is referred to be the fuel vendor (Westinghouse) as an Integral Fuel Burnable Absorber (IFBA).

3.2 IMPACTED MODEL AND CORRECTION IN THE TXU ELECTRIC LOCA METHODOLOGIES

The thin [ ]a,c boron coating on the fuel pellet surface is a burnable poison. Its only impact on LOCA analysis is that it affects the initial (pre-LOCA) gas content of the fuel rod, due to the helium generated as the coating is depleted with burnup. Therefore, only the RODEX2 code, which calculates the initial fuel rod conditions for both the SBLOCA and the LBLOCA, is potentially impacted.

Westinghouse calculates the helium released from the boron coating in its PAD 3.4 code as follows (Reference 9):

[

]a,c

[ ]a,b,c

[

]a,c

It would be a simple matter to modify RODEX2 to internally calculate and add this amount of He. However, instead of modifying this code, TXU Electric has elected to correct the number of moles calculated by RODEX2 by adding the He moles calculated manually (or by a utility code) using the above formulae and to input the corrected number of moles into the next steps (codes) in the LOCA methodology. This approach was tested by making two runs with the PAD 3.4 code. In the base case (case 9 in Table 4.1), the nominal values for the coating variables were input, and the code was allowed to calculate all fuel rod initial conditions which were then fed into the rest of the LBLOCA methodology. The PCT was then calculated. In the test case (case 6 in Table 4.1), the coating variables were set to zero, as they would be in

RODEX2, which does not have the capability to model this feature, but the calculated moles were manually corrected for the number of moles of He produced by boron depletion. The initial fuel rod conditions for the test case were then also fed into the rest of the LBLOCA methodology and the PCT was also calculated. The PCT in the base case differed from the test case PCT by approximately 4^0F, demonstrating that correcting the number of gas in moles in RODEX2 for the He generated by the boron coating depletion is a valid way to account for this fuel feature in the TXU Electric LOCA methodologies.

It should also be noted that this correction need only be applied for middle or end of life analyses. For beginning of life conditions, the depletion term DEPL above is near zero, so that the magnitude of the correction is negligible.

As a practical matter, the thin boron coating has no impact on the LOCA PCTs for either CPSES Unit 1 or Unit 2 because those PCTs have always occurred at the beginning of life where the coating has no impact on the analysis. To enable the TXU Electric LOCA methodologies to be applied to middle of life and end of life conditions, when the thin boron coating is present on the fuel, a correction is added to the number of gas moles calculated by RODEX2 and fed into the next steps of the methodology as initial conditions for the LOCA analysis. This correction is the number of He moles resulting from the depletion of the thin boron coating.

CHAPTER 4

RESULTS

Regarding the analyses being presented in this chapter, the beginning of life (BOL) cases, including the SBLOCA case, were performed with fuel of Framatome design where the only change between cases was to assume ZIRLO™ versus Zircaloy-4 cladding. Framatome designed fuel was used in the BOL cases in order to utilize the existing analyses of record, upon which the impact of methodology changes would be of interest since these were the highest PCTs. The end of life (EOL) cases were all performed with fuel of Westinghouse design. Here too, the differences between cases are only in the models, i.e., they compare ZIRLO™ versus Zircaloy-4 cladding, the presence or absence of the boron coating and/or both. Westinghouse designed fuel was used in the EOL cases, in part to illustrate the application of the methodology to fuel of different design, but also because methodology changes are more fully exercised at EOL since, several models (e.g., boron coating) are not significant at BOL and thus, the maximum impact of the model changes would be visible at EOL, with fuel of Westinghouse design. These combinations were deemed sufficient to illustrate the implementation of methodology changes.

In all cases, the comparisons focus on the effect of the TXU Electric Evaluation Model changes submitted in this report for USNRC approval. Clearly, fuel characteristics from the different vendors are different. Thus, comparisons of EOL to BOL cases would be between different fuel types, and thus, could potentially mask or at least distract from the effects of model changes. The focus of this report is methodology, so potential response differences due to fuel differences are not in the scope of the report. TXU has performed and will continue to perform LOCA analyses of its core designs at every reload, as needed. Nevertheless, informal application of the TXU LOCA methodology to Westinghouse fuel with ZIRLO™ cladding shows the range of possible responses is similar to that of Framatome fuel; although, the response in any given scenario may be different.

Lastly, detailed discussions of the accident progression including multiple sensitivities and plots of key variables have been provided in previous applications[4] for LBLOCA (Reference 1, Chapter 3) and for SBLOCA (Reference 5, Chapter 3) and to present them again would also detract from the main objective of this report.

Seven LBLOCA and two SBLOCA analyses are presented in this chapter. The results of these analyses are summarized in Table 4.1 and are presented to illustrate the following comparisons:

(a) The results of implementing the ZIRLO™ cladding models are compared (at end of life in Case 7 and at beginning of life in Case 10) to identical cases except that the Zircaloy-4 (Case 3 for end of life and Case 0 for beginning of life) models are used. No

[4]Case 18tda in this section is somewhat similar to the 3 inch break case of Reference 5 and Case 0 in this section is the same as the base case of Reference 1.

correction for the boron coating is made in any of these cases. The end of life Zircaloy-4 case has a 26^{0}F higher PCT (1721^{0}F versus 1695^{0}F). This difference is mostly in line with differences reported by CE (Reference 4, Table 6.5.1.3-3) for their end of life cases, where Zircaloy-4 had PCTs 7^{0}F, 13^{0}F and 105^{0}F higher[5] in three cases. The beginning of life ZIRLO™ case has a 9^{0}F higher PCT (1972^{0}F versus 1963^{0}F). This difference is also somewhat in line with differences reported by CE (Reference 4, Table 6.5.1.3-3) for their beginning of life cases, where ZIRLO™ had a PCT 12^{0}F higher in one case, 181^{0}F higher[5] in another and 58^{0}F lower in another. These cases demonstrate the proper implementation of ZIRLO™ cladding models into the TXU Electric LBLOCA methodology, for BOL and EOL as well as for fuel of Framatome and Westinghouse designs.

(b) The results of implementing the boron coating correction (Case 8) are compared to an identical case except that the boron coating is not modeled (Case 7). Both cases use the ZIRLO™ cladding models. It is seen that the corrected case has a 26^{0}F higher PCT (1721^{0}F versus 1695^{0}F). This case shows the separate effect of the boron coating. There are two other cases discussed below, Cases 6 and 9, that demonstrate the validity of the correction.

[5] The larger differences occurred for cases where the clad rupture occurred at significantly different stages of the event. This is not likely to occur with typical CPSES power shapes.

(c) The results of implementing both the ZIRLO™ cladding models and the boron correction (Case 8) are compared to an identical case except that the Zircaloy-4 models are used and the boron coating is not accounted for (Case 3). The PCTs for these cases are within approximately 1^0F of each other (1721^{0}F versus 1721^{0}F). This case shows that the combined effect of implementing both the ZIRLO™ cladding models and the boron correction is likely to be less than the effect of implementing each separately. Since TXU Electric fuel will have both features, these cases show that their combined effect on LBLOCA EOL results, which are expected to be the most impacted by the model changes being submitted in this report, is expected to be small, and in all likelihood, insignificant.

Two additional LBLOCA analyses are presented where the initial conditions were calculated with the Westinghouse fuel code PAD 3.4, instead of RODEX2, which is the TXU Electric methodology counterpart. These cases compare the results of implementing the boron coating correction (Case 9) to an identical case except that the boron coating is modeled by activating the proper options in PAD 3.4 (Case 6). Both cases use the ZIRLO™ cladding models. Although the PAD 3.4 code is not part of the TXU Electric methodology, the purpose of these cases is to demonstrate that correcting for the boron coating after running the fuel code gives essentially the same result as running the fuel code with the boron coating options activated, i.e., the PCTs are within 4 ^{0}F of each other. This means that correcting for the boron coating after the fuel code run, as described in Section 3.2, is an adequate way to account for the coating in the TXU Electric LOCA methodologies. TXU Electric considered substituting the PAD 3.4 code for its RODEX2 code. However, in order to remain consistent with and to be able to reproduce and evaluate sensitivities involving results of past analyses, and because the combined methodology changes for ZIRLO™ and the boron coating are not significant, it is clearly preferable to remain with RODEX2 and correct results as indicated. This choice is reinforced by the observation that differences in PCT are slightly although not significantly greater between the same case run with the different fuel codes than between different cases run with the same fuel code. For example, Cases 6 and 8 are the same case run with PAD 3.4 versus RODEX2 and show the RODEX2- based PCT to be 29 ^{0}F higher. In contrast, the difference between ZIRLO™ and Zircaloy-4, i.e. between Cases 3 and 7 is 26 ^{0}F for RODEX2 and less in preliminary PAD 3.4 calculations. Finally, the choice to remain with RODEX2 is conservative, i.e., it is further justified by the fact that RODEX2 consistently gives higher PCTs than PAD 3.4 for the same cases.

TABLE 4.1

Comparison of TXU Electric's Methodology LOCA Analysis Results Using ZIRLO™ versus Zircaloy-4 Models plus with versus without Correction for Boron Coating

Case #	Fuel Code	Correction for boron Coating	Cladding Material	LOCA ANALYSIS RESULTS		
				PCT	Node Oxid.	Pin Oxid.
3	RODEX2	NO	Zircaloy-4	1721^{0}F	1.946%	0.283%
7	RODEX2	NO	ZIRLO™	1695^{0}F	1.284%	0.247%
8	RODEX2	YES	ZIRLO™	1721^{0}F	1.568%	0.266%
9	PAD 3.4	NO (by code[6])	ZIRLO™	1696^{0}F	1.264%	0.235%
6	PAD 3.4	YES	ZIRLO™	1692^{0}F	1.256%	0.228%
0[7]	RODEX2	NO (BOL)	Zircaloy-4	1963^{0}F	3.195%	0.504%
10	RODEX2	NO (BOL)	ZIRLO™	1972^{0} F	3.537%	0.517%
18tda	RODEX2	NO (BOL)	Zircaloy-4	1859^{0}F[8]	1.994%	0.300%
18tda	RODEX2	NO (BOL)	ZIRLO™	1866^{0}F	2.047%	0.303%

[6]The PAD 3.4 code has the models to calculate the effects of the boron coating. Case 9 has the models turned on while Case 6 has them off. The results of Case 6 are manually corrected after the PAD 3.4 run and the corrected results are passed on to the next stages of the LOCA analysis, as shown in Section 3.2. The similarity of results between Cases 9 and 6 demonstrates that this manual correction technique is adequate. The manual correction is also implemented in the other cases labeled "yes" in this column.

[7]Unit 1 Cycle 8 analysis of record (Table 4.1 of Reference 1). The BOL cases, including the SBLOCA are also for Framatome fuel, while all the EOL cases are for Westinghouse fuel.

[8]Temperatures are higher than LBLOCA Cases 3,7,8,9 and 6 in part because those are end of life cases, whereas the SBLOCA cases are beginning of life. More significantly though, the fuel analyzed for the SBLOCA was Framatome fuel (although ZIRLO™ was used instead of Zircaloy-4 for evaluation model comparisons), whereas the fuel analyzed for the LBLOCA cases was Westinghouse (although Zircaloy-4 was used instead of ZIRLO™ and the boron coating was omitted for evaluation model comparisons). Framatome fuel's smaller diameter is the primary reason for the higher PCT. Burnup is secondary.

CHAPTER 5

CONCLUSION

The objective of this report is to obtain USNRC approval of changes to TXU Electric's ECCS Evaluation Models so they may be used to analyze fuel with ZIRLO™ cladding and/or with the fuel pellets coated with boron[9]. ZIRLO™ cladding models (and/or the acceptance of the applicability of existing Zircaloy-4 models) and boron fuel coating models have been implemented into TXU Electric's large and small Break LOCA USNRC-approved ECCS Evaluation Models (References 1 and 5).

The models for the ZIRLO™ cladding are described in Chapter 2 and are essentially the same as those by the fuel assembly vendor. The boron fuel coating model is described in Chapter 3 and is also essentially the same as that used by the fuel vendor. In addition to the many sensitivity studies discussed in Chapter 2, nine LOCA analyses were presented in Chapter 4 to demonstrate various aspects of TXU Electric's implementation:

1. The effect of ZIRLO™ cladding in comparison to Zircaloy-4 cladding (i.e., all cladding models implemented at once) in large break LOCA analyses at beginning of life and at

[9]These features of Westinghouse Electric Corporation fuel products may be present in future fuel assemblies for CPSES, and therefore need to be incorporated into TXU Electric's large and small break LOCA ECCS Evaluation Models.

end of life. The end of life case shows a PCT difference of about 26^{0}F and the beginning of life a difference of 9 ^{0}F, (with ZIRLO™ lower in both cases).

2. The separate effect of the boron fuel coating in comparison to not having such a coating in large break LOCA analyses at end of life. The end of life difference was also of about 26^{0}F, (with the coating tending to increase the PCT). The coating has no effect at beginning of life, which has always been the most limiting condition for CPSES.

3. The combined effect of both ZIRLO™ cladding together with the boron fuel coating in comparison to Zircaloy-4 cladding where the fuel has no such a coating, in large break LOCA analyses at end of life. Although the previous differences were already minor, the difference of the combined cases was less than 1^{0}F.

4. The effect of ZIRLO™ cladding in comparison to Zircaloy-4 cladding in small break LOCA analyses at beginning of life. This case shows a PCT difference of about 7^{0}F, (with ZIRLO™ higher) .

These analyses demonstrate the proper implementation of the changes described in Chapters 2 and 3 and the overall conclusion from these analyses is that the changes to the methodologies are not significant, whether taken separately or together.

TXU Electric will therefore incorporate these changes into its large and small break LOCA methodologies to account for ZIRLO^{TM} cladding and/or boron fuel coating as needed. These changes include all codes, input decks, results, conclusions, and application procedures presented in this report to perform large and small break LOCA analyses and evaluations in compliance with 10 CFR 50.46 criteria and Appendix K requirements, for CPSES 1 and 2.

CHAPTER 6

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