Enclosure 2

TECHNICAL EVALUATION REPORT

TECHNICAL EVALUATION REPORT OF THE FROSSTEY2 FUEL PERFORMANCE CODE

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NOMENCLATURE

BOC	beginning-of-cycle
BWR	boiling-water reactor
CFR	Code of Federal Regulations
DNBR	departure from nucleate boiling ratio
EOC	end-of-cycle
EOL	end-of-life
GE	General Electric Company
LHGR	linear heat generation rate
LOCA	loss-of-coolant accident
LWR	light-water reactor
MCPR	minimum critical power ratio
NRC	U.S. Nuclear Regulatory Commission
PNL	Pacific Northwest Laboratory
PWR	pressurized-water reactor
SAR	safety analysis review
SER	safety evaluation report
SRP	safety review plan
TER	technical evaluation report
VYNPC	Vermont Yankee Nuclear Power Corporation
YAEC	Yankee Atomic Electric Company

CONTENTS

1.0 INTRODUCTION

The thermal and mechanical performance of fuel in a light-water reactor (LWR) during its operational lifetime must be described in the safety analysis of the loss-of-coolant accident (LOCA) as well as for other accidents, transients, and normal operation. The determination of stored energy and rod pressures for the LOCA analysis and other analyses requires a fuel pin thermal performance model that is capable of calculating fuel and cladding behavior, including the gap conductance between the fuel and cladding, as a function of burnup. The parameters affecting fuel performance, such as fission gas release, cladding dimensional changes, fuel densification, fuel thermal expansion, and fuel swelling, should be accounted for in the model.

The FROSSTEY2 fuel performance code has been submitted by Vermont Yankee Nuclear Power Corporation (VYNPC) to the Nuclear Regulatory Commission (NRC) for approval to apply this code to analysis of LOCA initial conditions, initial conditions for transient and end-of-life (EOL) limiting analyses.

The original FROSSTEY fuel performance code was submitted by the Yankee Atomic Electric Company (YAEC) in References 2 and 3 and supplemented in Reference 4. However, the NRC approval of this code (Reference 5) limited its use to non-LOCA analyses at low-to-moderate exposure ranges for both pressurized-water reactor (PWR) and boiling-water reactor (BWR) applications. Therefore, the original code was not applicable to high burnup or LOCA applications.

The FROSSTEY2 fuel performance code (Reference 1) is a reformulation of the FROSSTEY code and has been verified with high-burnup data in order to remove the earlier restrictions. Changes in the FROSSTEY2 fuel performance code, relative to the original submittal in References 2, 3, and 4, are primarily in the models for fission gas release, fuel thermal conductivity, fuel relocation, and flux depression across the fuel pellet. In addition, material properties for UO_2-Gd_2O_3 were included in FROSSTEY for burnable poison rods but were not formally reviewed in the original FROSSTEY submittal (Reference 5). These same material properties for burnable poison rods are included in FROSSTEY2 and approval for use is included in the VYNPC submittal to the NRC. Therefore, based on the model changes and requested approval for applications, this Technical Evaluation Report (TER) of the FROSSTEY2 code is divided into seven major sections: Fission Gas Release, Fuel Thermal Conductivity and Fuel Relocation, Flux Depression, Comparison of Code Thermal Predictions to Data, Gadolinia Burnable Poison (UO_2-Gd_2O_3) Properties, Application of Code for Licensing Analyses, and Conclusions. During the course of this review VYNPC changed the solid gap conductance model and this change will be discussed in the section entitled Comparison of Code Thermal Predictions to Data.

Pacific Northwest Laboratory (PNL) has acted as a consultant to the NRC in this review. As a result of the NRC staff and their PNL consultant's review of the submitted report (Reference 1), a list of questions requesting clarification was sent by the NRC to VYNPC (References 6 and 7). VYNPC responded to those questions in References 8 and 9. A review of the responses concluded that VYNPC had not provided sufficient information on how they intended to apply the code for LOCA analyses nor did they adequately address the problems with the code predictions of fission gas release and fuel temperatures (Reference 10). Some of the questions from the original requests (References 6 and 7) were restated in Reference 10 to gain further information on FROSSTEY2 code applications for licensing analyses and identified those responses (References 8 and 9) that were unsatisfactory or incomplete. VYNPC responded partially to these questions in References 11 and 12; however, complete responses to all questions that superseded those in References 11 and 12, were provided in Reference 13. A review of these second round responses concluded that the changes made by VYNPC had resolved the problems with the code predictions of fission gas release and fuel temperatures, but that the code was not being applied in a conservative manner consistent with previous NRC approvals for LOCA analysis methods using best estimate codes. Therefore, a summary of different analytical approaches for maintaining conservatisms in code predictions of stored energy for input to LOCA analyses was provided by PNL in Reference 14 for guidance to VYNPC. In addition, a brief summary of the status of this review was provided in Reference 15, along with a restatement of the unresolved issue, i.e., the lack of conservatism in

FROSSTEY2 applications to licensing analyses. In order to try and resolve those unresolved issues, VYNPC submitted responses in References 16 and 17. PNL has completed the review and written this TER based on References 1, 8, 9, 11, 12, 13, 16, and 17.

2.0 FISSION GAS RELEASE

The review of the original FROSSTEY2 submittal (Reference 1) revealed that the code underpredicted fission gas release data for particular conditions. VYNPC was questioned about this underprediction and was asked to supply information on individual measured data and code predictions of these data (References 6 and 7). A review of the fission gas release data supplied in VYNPC's responses revealed that the code significantly underpredicted both steady-state and transient release data above a critical level of release. Release values above this critical level are important for predicting EOL rod pressures at extended-burnup levels. VYNPC implied in their response (Reference 8) that this underprediction was acceptable because the uncertainty in the data did not allow for a more accurate prediction.

PNL's review of this response indicated that other fuel vendor's fuel performance codes have been able to provide a much better prediction of this same fission gas release data than that provided by FROSSTEY2 (Reference 10). Therefore, it was concluded by PNL that the FROSSTEY2 underprediction of fission gas release was unacceptable and, therefore, must be resolved before the code could be approved for licensing analyses of EOL rod pressures. It was further concluded that VYNPC needed to account for uncertainties in both the steady-state and transient power histories that are used for licensing analyses, such as for calculating EOL rod pressures. VYNPC was requested (Reference 10) to provide a second round of responses in order to address the unresolved issues on fission gas release and power histories in the first round of responses.

VYNPC responded, based on the second round questions, by altering the fission gas release, solid gap conductance, fuel relocation, and fuel thermal conductivity models (Reference 13). These changes resulted in the code, on the average, overpredicting fission gas release data under both steady-state and transient, i.e., power bumping, rod power conditions. The methodology proposed by VYNPC for determining the rod power histories for the EOL rod pressure analyses were also found to be conservative. Therefore, PNL concludes that the methodology described by VYNPC for determining EOL rod pressures is satisfactory for licensing analyses. However, because the verification of the model is limited to data with maximum rod-average burnup levels of 60 GWd/MTM (approximate peak pellet is 66 GWd/MTM for a BWR), it is recommended that the code be limited to a rod-average burnup level of 60 GWd/MTM for both BWR and PWR applications.

3.0 FUEL THERMAL CONDUCTIVITY AND RELOCATION

The fuel thermal conductivity and relocation models are two of the most important for predicting fuel temperatures, along with the fuel-to-cladding gap conductance model. These two models are generally two separate independent models in most fuel performance codes. However, in the original FROSSTEY2 code (Reference 1) they were empirically related to each other to give a best estimate prediction of a given set of measured centerline temperature data. This original version of FROSSTEY2 assumed that the fuel relocated to eliminate the fuel-to-cladding gap. This resulted in a high gap conductance, i.e., small temperature delta T across the gap. The fuel thermal conductivity was then decreased in order to raise the delta T across the fuel a corresponding amount and, thus, result in a match to the measured fuel centerline data. Therefore, the FROSSTEY2 code assumed that most of the delta temperature drop existed across the fuel pellet and only a small delta temperature drop existed across the fuel-to-cladding gap.

This assumption is significantly different from the previous FROSSTEY code (References 2 and 3), the GT2R2 code (Reference 18) used by NRC for auditing industry codes, and current fuel vendor codes. It should also be noted that this assumption reduces the calculated stored energy for LOCA. A fuel performance code entitled ESCORE (Reference 19), that has been submitted to NRC for licensing applications, has made a similar assumption regarding fuel relocation and thermal conductivity. The NRC Safety Evaluation Report

(SER) (Reference 20) has concluded that the increase in fuel relocation and corresponding decrease in fuel thermal conductivity was not appropriate for licensing applications because of the high degree of uncertainty in the data that are claimed to support these changes. It was concluded (Reference 10) that the fuel relocation and thermal conductivity models in FROSSTEY2 were not appropriate for licensing applications for the same reasons as discussed in the NRC SER of the ESCORE code (Reference 20).

VYNPC responded in their second round of responses (Reference 13) by stating that the changes to the fuel relocation model were removed and the current FROSSTEY2 models were identical to the FROSSTEY models (References 2 and 3). VYNPC also claimed that these changes made the FROSSTEY2 code somewhat conservative in predicting fuel temperatures. However, examination of FROSSTEY2 predictions of the latest experimental centerline temperature data from fuel rods typical of commercial fuel designs and at linear heat generation rates (LHGRs) important to licensing applications, i.e., >10 kW/ft, the code appears to provide either a slight underprediction or a best estimate prediction of fuel centerline temperatures at low-to-moderate burnup levels (see Figures 2a-1, 2a-4, 2a-7, and 2a-10 of Reference 13). The changes to the fuel relocation and thermal conductivity models (Reference 13) in the FROSSTEY2 code are acceptable for licensing applications if the code is applied using a conservative methodology for calculating fuel temperatures as discussed in Sections 5.0 and 7.0.

4.0 FLUX DEPRESSION

The FROSSTEY2 code includes the RADAR model for calculating the radial power profile across the fuel pellet due to flux depression (Reference 1). The RADAR model was originally developed by British Nuclear Fuels Limited (Reference 21) and is currently used in the NRC audit code GT2R2 (Reference 18). PNL has performed comparisons of RADAR calculated radial power distributions to those calculated with more sophisticated and accurate physics codes. These comparisons have demonstrated that the RADAR code becomes less accurate as fuel burnup levels increase because it fails to accurately predict the plutonium buildup at the fuel surface and, therefore, RADAR underpredicts power production at the surface. PNL has also evaluated the error in calculated fuel centerline temperature due to the underprediction and found less than a 1% error at a rod-average burnup level of 50 GWd/MTM. Therefore, PNL concludes that the use of the RADAR model is satisfactory for licensing applications. However, it is recommended that the FROSSTEY2 code be limited to a rod-average burnup level of 60 GWd/MTM for licensing applications.

5.0 COMPARISON OF CODE THERMAL PREDICTIONS TO DATA

The FROSSTEY2 submittal (Reference 1) provided a comparison of FROSSTEY2 predicted versus measured centerline temperatures but did not identify the specific data on the plots. This prevented PNL and NRC reviewers from identifying how well the code predicted particular experimental fuel rod data. The ability to make this distinction was important because some of the data are judged to be more applicable to verification of fuel performance codes used for licensing applications than other data. Those specific data judged to be more applicable are those from experimental fuel rods typical of today's fuel designs, operating at LHGRs typically used for licensing calculations, and the best characterized and reliable experimental data, i.e., the most recent temperature data from Halden experimental programs. Therefore, VYNPC was requested (References 6 and 7) to provide FROSSTEY2 code predictions of Halden measured centerline temperature data from experimental assemblies IFA-432 and IFA-513. VYNPC responded to this request by supplying FROSSTEY2 predictions of Rods 1, 2, 3, 5, and 6 of IFA-432 and Rods 1, 2, and 6 of IFA-513; however, the corresponding measured data were not supplied (References 8 and 9).

Examination of the FROSSTEY2 code predictions in Reference 8 indicated that FROSSTEY2 underpredicted the measured temperatures for Rod 3 of IFA-432 when burnup levels exceeded 15 to 20 GWd/MTM. VYNPC was questioned on the reason for this underprediction (Reference 10). In the second round of responses, VYNPC replied that the underprediction was due to unrealistically high interfacial pressures predicted by the code between the fuel and cladding as burnup levels increased. Consequently, this led to unrealistically high gap conductance values (Reference 13). VYNPC has reduced the maximum possible interfacial pressures in the code by a fractional amount of the original FROSSTEY2 calculational values. This has resulted in a conservative over-prediction of centerline temperatures for Rod 3 of IFA-432.

VYNPC has implied (Reference 13) that by changing the fuel relocation and thermal conductivity models in FROSSTEY2 to be the same as those in FROSSTEY (see discussion in the Fuel Relocation and Thermal Conductivity section of this report) that the code provides a more conservative prediction of fuel thermal conditions than for the original FROSSTEY2 code submitted in Reference 1. PNL acknowledges that this may be true for volume average fuel temperatures, i.e., fuel stored energy, but can not be verified. However, from examination of the fuel centerline predictions in Figures 2a-1 through 2a-12 of Reference 13, it is judged that the current FROSSTEY2 code provides a best estimate prediction of fuel centerline temperatures from experimental fuel rods typical of today's commercial fuel designs. PNL, therefore, concludes that the FROSSTEY2 code is primarily a best estimate code and may be applied to predicting fuel thermal conditions in licensing applications if used in a conservative manner in the following two areas: 1) account for uncertainties in the code input (e.g., uncertainties in fuel dimensions, fuel rod dimensions, and operating conditions) and 2) uncertainties in the code predictions. The conservatisms that must be applied in licensing applications are discussed further in the section entitled Application of Code for Licensing Analyses.

6.0 GADOLINIA BURNABLE POISON (UO_2-Gd_2O_3) PROPERTIES

VYNPC uses General Electric Company (GE) UO_2-Gd_2O_3 properties that have previously been reviewed and approved by NRC (Reference 22). Therefore, these properties do not need to be reviewed again; however, the methodology of applying the FROSSTEY2 code and the UO_2-Gd_2O_3 properties for evaluating burnable poison rod behavior for licensing analyses does need to be reviewed. The application of FROSSTEY2 for evaluating burnable poison rod analyses is the same as for evaluating fuel rods and will be reviewed in the following section.

7.0 APPLICATION OF CODE FOR LICENSING ANALYSES

VYNPC was requested to supply information in the first round of questions (References 6 and 7) on how they planned to maintain their technical expertise in the use of FROSSTEY2 for licensing applications. VYNPC responded that YAEC has maintained a fuel modeling function for over 15 years and during this time have maintained procedures for FROSSTEY and GAPEX code applications. VYNPC intends to establish similar procedures for FROSSTEY2 applications based on NRC's approval of the code. VYNPC has further indicated that currently more than eight engineers in their organization have experience in fuel performance code use. PNL concludes that VYNPC has a plan to maintain technical expertise in the use of FROSSTEY2 for licensing applications and that this plan is acceptable.

The application of a best estimate code for licensing analyses requires, as noted above, that code input uncertainties and code calculational uncertainties must be applied in a conservative manner. VYNPC was requested to provide FROSSTEY2 calculational examples of how the code was to be applied for each licensing application and identify the conservatisms in their code input (References 6 and 7). In addition, VYNPC was requested to provide a description of the analysis methodology that demonstrates that the code application is conservative and bounding for each licensing application, e.g., LOCA, EOL rod pressure, cladding strain, fuel melting, minimum critical power ratio (MCPR) for BWR, and departure from nucleate boiling ratio (DNBR) for PWR analyses, and to quantify conservatisms. The analysis application for burnable poison rods is the same as for fuel rods. The use of the same analysis approach for both burnable poison rods and fuel rods is acceptable.

VYNPC's response was reviewed (References 8 and 9) and it was concluded that the description of the conservatisms applied to the FROSSTEY2 code for determining the stored energy for input to the LOCA analysis were not adequately identified. Therefore, VYNPC was again requested to identify and quantify the conservatisms applied to the code predictions and code input for calculating stored energy for LOCA (Reference 10). It was also suggested that VYNPC use the code comparisons to centerline temperature data for quantifying the code calculational uncertainties and for quantifying the conservatisms that need to be applied to the code's best estimate prediction of fuel stored energy. In the second round of responses VYNPC provided example FROSSTEY2 calculations for input to LOCA utilizing both nominal, i.e., best estimate, input values and licensing, i.e., conservative, input values but provided no estimate of the code calculational uncertainties (Reference 13).

PNL provided a detailed description in Reference 14 of those conservatisms that are required for utilizing best estimate fuel performance codes to calculate fuel stored energy for LOCA. In summary, those conservatisms are: 1) use of maximum LHGRs allowed by plant technical specifications as code input; 2) use of worst case fuel rod dimensions as allowed by fabrication specifications as code input; and 3) application of code calculational uncertainties, i.e., 95% upperbound probability at a 95% confidence level, to the code's best estimate prediction of stored energy.

Following two conference calls with VYNPC, it became apparent that VYNPC only intended to apply input uncertainties to FROSSTEY2 for determining fuel stored energy for input to LOCA analyses. VYNPC believed that the conservatisms applied to the input for the FROSSTEY2 code more than compensated for the code calculational uncertainties. PNL prepared a letter (Reference 15) that examined VYNPC's claim that the FROSSTEY2 codes conservative input more than compensated for the code's calculational uncertainties, i.e., σ code input >> σ code calculation. PNL concluded (Reference 15) that VYNPC's claim of adequate conservatisms was not valid because the FROSSTEY2 code input uncertainties were approximately equal to the code calculational uncertainties.

VYNPC provided a third round of responses (Reference 16) to address the FROSSTEY2 calculational conservatisms for licensing applications for LOCA. This third set of responses for LOCA application was reviewed and discussed with staff from VYNPC and NRC, and NRC's consultant from PNL, at a meeting that was held at NRC Headquarters on April 7, 1992. From this meeting, the NRC staff and their PNL consultant concluded that the basic approach used by VYNPC for determining experimental uncertainties and FROSSTEY2 code calculational uncertainties was acceptable with two exceptions. The first exception recommended a deletion and an addition to the experimental rods used in the VYNPC fuel temperature data base. The second exception recommended that VYNPC include the response surface uncertainty in their estimate of FROSSTEY2 code uncertainty. At the conclusion of this meeting, VYNPC was requested to provide a fourth set of responses with these revisions to their calculation of LOCA-stored energies and to provide a description of how FROSSTEY2 would be applied for non-LOCA applications.

The fourth set of VYNPC responses (Reference 17) with the above requested revisions in order to resolve the two exceptions for code application to LOCA-stored energy was found to be satisfactory. The responses for non-LOCA application have one particular common problem with the methodology that will be discussed at this time. Those code methodologies for non-LOCA applications that are unique to the particular analysis will be discussed in the sub-sections for those analyses, e.g., EOL rod pressure, cladding strain, fuel melting, gap conductances for transient analyses, and fuel temperatures for physics analyses.

The common VYNPC methodology for all non-LOCA analyses is the use of nominal fabricated dimensional values for input to FROSSTEY2. This use of nominal fabricated input is satisfactory for calculating core average conditions such as for core average fuel temperatures for physics analyses and core average gap conductances for departure from nucleate boiling analyses. However, this is not satisfactory for "hot channel or high power rod" analyses, e.g., for EOL rod pressure, cladding strain, fuel melting, and hot channel gap conductances for transient analyses.

Previously approved NRC methodologies for the "hot channel or high power rod" analyses from the fuel vendors have required that bounding fabricated dimensions be used to provide conservative output results for the specific analysis. Therefore, it is recommended that for hot channel or high power rod analyses that VYNPC use either bounding fabricated specifications for input to these analyses or account for the fabrication uncertainties in the output results as done for the LOCA analyses. Therefore, the code predictions of EOL rod pressure, cladding strain, fuel melting, and hot channel gap conductances for transient analyses are to be appropriately conservative based on the uncertainties in the input values. This specific issue for each application is also discussed in the following Sections 7.1, 7.2, 7.3, and 7.4.

7.1 END-OF-LIFE INTERNAL ROD PRESSURES

The input power history for calculating EOL internal rod pressures is one of the most important input parameters for this analysis. VYNPC has proposed to use a maximum expected bounding rod power history with a nominal axial power shape based on physics reload analyses for the plant/cycle in question. In order to simulate transient power operation, VYNPC superimposes a significant number of transient axial power shapes throughout the irradiation life of the bounding power rod that allows the peak node to be at the maximum LHGR technical specification limit (MAPLHGR for a BWR and the F_Q limit for a PWR) for a brief period for each reload analyses. This VYNPC power history allows for a conservative prediction of fission gas release for the peak operating rod in the core and, therefore, is satisfactory for this licensing application.

The FROSSTEY2 code-calculated parameters that are important to the determination of the rod internal pressures are fission gas release and internal rod void volume. As noted earlier in Section 2.0, Fission Gas Release, the FROSSTEY2 code provides a conservative overprediction of fission gas release. PNL has concluded that the code's overprediction of fission gas release covers the code's calculational uncertainties of this prediction.

The original comparison of FROSSTEY2 predictions to internal rod void volume data as measured from high-burnup fuel rods, provided in Reference 13 per NRC's request in Reference 10, demonstrated that the code significantly underpredicted internal rod void volumes. This underprediction results in a significant degree of conservatism in the FROSSTEY2 rod pressure calculation. However, as a result, VYNPC made a correction to the calculation of dish volume in the FROSSTEY2 code that provides a much better comparison to measured data (as shown in Figure 3.11 in Reference 16). VYNPC has claimed that the FROSSTEY2 code still provides a slight (conservative) underprediction of internal void volume (Reference 17). PNL concludes that the use of bounding fabricated values for plenum and dish volumes as recommended above will adequately cover the code calculational uncertainties in void volumes. In addition, the use of lower or upper bounding values of fuel-to-cladding gap size for the rod pressure calculation should be based on those gap size values based on uncertainties in rod fabrication that provide the most conservative (highest) prediction of rod pressures.

Therefore, PNL concludes that FROSSTEY2 calculational uncertainties in internal rod pressures are adequately covered by inherent conservatisms in the code, the power history (steady-state and transient), and the above recommended uncertainties in fabrication for input to the code.

7.2 CLADDING STRAIN

The input steady-state power history used for the FROSSTEY2 calculation of cladding plastic strain is the same as the bounding power history used for the EOL rod pressure analysis with power ramping up to the power level that results in 1% plastic strain at periodic burnup levels. This technique is used to determine the power level of the 1% plastic strain limit, per the NRC Safety Review Plan (SRP) (Reference 23). PNL concludes that this analysis methodology is satisfactory when conservatively bounding uncertainties due to fabrication inputs to FROSSTEY2 are applied, per the recommendations given above.

7.3 FUEL CENTERLINE MELTING

The input power history used for the FROSSTEY2 calculation of fuel melting is similar to that used for cladding strain except the periodic ramped powers are taken to the point of fuel melting. In addition, VYNPC takes into account the uncertainties in FROSSTEY2 calculated fuel centerline temperatures at a 95% probability with a 95% confidence level for fuel melting in the same manner as the FROSSTEY2 application to LOCA-stored energy with the exception that nominal fabrication input data are used. As noted earlier, PNL recommends that VYNPC also utilize conservatively bounding uncertainties due to fabrication input to FROSSTEY2 are applied for the fuel melting calculation as done for LOCA applications.

PNL concludes that this analysis methodology is satisfactory when conservatively bounding uncertainties due to fabrication inputs to FROSSTEY are applied per the recommendations in the above paragraph.

7.4 GAP CONDUCTANCE FOR TRANSIENT ANALYSES

Core reload analyses require that all Safety Analysis Review (SAR) transients are analyzed to determine the MCPR limits for BWRs and DNBR limits for PWRs at various exposures for each cycle. These transient analyses are divided into core-wide system responses and a hot channel response that require estimates of the core-wide gap conductance and the hot channel gap conductance. At this point, it should be stressed that the FROSSTEY2 gap conductance model itself is satisfactory for this application, however, the issue is in the code application that involves the use of a nominal fabrication input for hot channel analyses, and a constant axial power shape for all exposures at steady-state initial conditions prior to the transient (for BWRs). It is noted that the FROSSTEY2 code is only used for initial steady-state conditions prior to the transient. However, it should also be noted that the use of a constant axial power shape and axial gap conductance during the transient for delta-CPR analyses may also not be appropriate for some BWR fuel designs.

The VYNPC methodology for the use of FROSSTEY2 for determining the core-wide gap conductance is based on nominal fabrication input values and a volumetrically-weighted average gap conductance of each of the fuel types in the core and a constant axial power shape for both BWRs and PWRs. The use of nominal fabrication input values is acceptable for determining core wide gap conductance for both BWR and PWR applications because this is an average value for the whole core. However, the use of constant power shapes is judged to be acceptable only for PWR applications. The use of constant axial power shapes is not acceptable for all BWR designs because the steady-state core axial power shape can change significantly from beginning-of-cycle (BOC) to end-of-cycle (EOC) and this change may be different for different fuel designs. It is also noted that the axial power shape will also change during the course of a transient. The magnitude of this change in axial power shape from steady-state operation during the cycle is dependent on the BWR fuel design, axial variations in enrichment, core loading pattern, and control blade withdrawal pattern. The change in axial power shape during a transient is also dependent on these same factors, but in addition the power magnitude and the duration of the transient is dependent on the initial steady-state axial shape and the type of transient. The NRC is aware that core and hot bundle axial power shape changes can significantly impact delta-CPR calculational results for some BWR fuel designs and transient types. Based on this NRC experience, PNL recommends that VYNPC include the changes in steady-state axial power shape during the cycle exposure for initialization of the transient and also the change in core axial power shape during the transient for determining delta-CPR limits with exposure for BWRs.

The VYNPC methodology for determining the hot channel gap conductance is to use nominal as-fabricated input values, and assume that the peak node is operating at the maximum average planar linear heat generation rate (MAPLHGR) limit for the BWR and that the peak node and rod radial powers are at the technical specification limits for a PWR. The axial power shapes for both BWRs and PWRs are a constant chopped cosine. This is acceptable for PWR applications, however, this may not be conservative for determining delta-CPR limits for BWRs because, as noted above, the BWR change in axial power shape for initial steady-state and transient conditions can impact delta-CPR results. Therefore, PNL recommends that VYNPC include the changes in steady-state and transient axial power shapes and the associated change in axial gap conductance during steady-state and transient conditions with exposure in their hot channel analyses of delta-CPR. For the hot channel gap conductance at each exposure level, VYNPC calculates an axially-dependent gap conductance for each rod type in a BWR bundle and each axial rod type segment is averaged to produce an axially dependent gap conductance. The VYNPC methodology for calculating the hot channel gap conductance for a PWR is based only on the limiting rod in the bundle and is a power-weighted average of each of the axial segments in the limiting hot rod. Both of these averaging techniques for gap conductance of the limiting bundle and rod are acceptable for BWR and PWR applications, respectively.

In summary, PNL concludes that the VYNPC methodology for determining hot channel gap conductance for PWRs is acceptable when conservatively bounding uncertainties due to fabrication are applied per the above recommendations. The VYNPC methodology for calculating hot channel gap conductance for MCPR limits for BWRs is also found to be acceptable when conservatively bounding uncertainties due to fabrication are applied and the hot channel axial gap conductance is determined based on the change in axial power shape during steady-state and the transient for the delta-CPR analysis. In addition, PNL recommends that VYNPC model the change in both initial steady-state and transient axial power shape with exposure for the delta-CPR analysis.

7.5 FUEL TEMPERATURE FOR PHYSICS ANALYSES

The VYNPC physics code which calculates the three-dimensional core response to reactivity changes uses a volume average fuel temperature relationship versus power at various exposure intervals. This volume average fuel relationship versus rod power at different exposures for different fuel types is to be calculated with FROSSTEY2 using an average of axial power shapes from previous applicable cycles. PNL concludes that this analysis methodology is satisfactory for application to physics calculations because high accuracy in fuel temperatures is not required for this calculation.

8.0 CONCLUSIONS

PNL has reviewed the documentation on the application of the FROSSTEY2 fuel performance code to LOCA and non-LOCA licensing analyses (References 1, 8, 9, 11, 12, 13, 16, and 17) in accordance with Section 4.2 of the SRP. PNL concludes that the FROSSTEY2 code is acceptable for licensing applications with the following recommended conditions.

1. The FROSSTEY2 code is to be used for licensing applications only up to a maximum rod-average burnup level of 60 GWd/MTM per recommendations in Sections 2.0 and 4.0 for both BWRs and PWRs.

2. Non-LOCA applications that involve the hot channel or peak power rod shall use either bounding fabricated specifications for input or, as done in the VYNPC LOCA analysis, account for the uncertainties in fabrication in a manner conservative to the analysis results, i.e., internal rod pressure, cladding strain, centerline temperature, and gap conductance results per Section 7.0.

3. For calculation of core wide and hot channel gap conductances for determining BWR MCPR limits, VYNPC needs to include the effect of changes in axial power shape with exposure on delta-CPR limits for each BWR design utilized by VYNPC per Subsection 7.4. The FROSSTEY2 code is only used for steady-state calculations and, therefore, the FROSSTEY2 initialization of fuel temperatures and gap conductance for the delta-CPR analysis needs to include the change in axial power shape with exposure during steady-state operation.

9.0 REFERENCES

1. Letter, L. W. Capstick (VYNPC) to V. L. Rooney (NRC). December 16, 1987. Subject: Vermont Yankee LOCA Analysis Method FROSSTEY Fuel Performance Code (FROSSTEY2). Letter number FVY 87-116, Vermont Yankee Nuclear Power Corporation, Vermont.

2. Letter, D. E. Vandenberg (YAEC) to Office of Nuclear Reactor Regulation (NRC). May 18, 1981. Subject: Submittal of Documentation of YAEC Fuel Performance Code (FROSSTEY) YAEC-1249P, entitled "Methods for the Analysis of Oxide Fuel Rod, Steady-State Thermal Effects (FROSSTEY)." Letter number FVY 81-82. Yankee Atomic Electric Company, Framingham, Massachusetts.

3. Schultz, S. P., and K. E. St. John. June 1981. *Methods for the Analysis of Oxide Fuel Rod Steady-State Thermal Effects (FROSSTEY) Code Qualification and Application*. YAEC-1265P, Yankee Atomic Electric Company, Framingham, Massachusetts.

4. Letter, L. H. Heides (YAEC) to D. G. Eisenhut (NRC). March 17, 1983. Subject: Response to Questions on Yankee Atomic Electric Company Fuel Performance Code (FROSSTEY). Letter number FVY 83-22, Yankee Atomic Electric Company, Framingham, Massachusetts.

5. Letter, D. B. Vassallo (NRC) to R. W. Capstick (VYNPC). September 27, 1985. Subject: Approval of Use of Fuel Performance Code FROSSTEY. U.S. Nuclear Regulatory Commission, Washington, D.C.

6. Letter, M. B. Fairtile (NRC) to R. W. Capstick (VYNPC). May 2, 1989. Subject: Request for Additional Information - FROSSTEY2 Fuel Performance Code (TAC No. 68216). U.S. Nuclear Regulatory Commission, Washington, D.C.

7. Letter, M. B. Fairtile (NRC) to R. W. Capstick (VYNPC). May 24, 1989. Subject: Second Request for Additional Information - FROSSTEY2 Fuel Performance Code (TAC No. 68216). U.S. Nuclear Regulatory Commission, Washington, D.C.

8. Letter, R. W. Capstick (VYNPC) to Document Control Desk (NRC). July 14, 1989. Subject: Response to NRC Request for Additional Information on the FROSSTEY2 Fuel Performance Code. Letter number BVY 89-65, Vermont Yankee Nuclear Power Corporation, Vermont.

9. Letter, R. W. Capstick (VYNPC) to Document Control Desk (NRC). August 4, 1989. Subject: Supplemental Information on the FROSSTEY2 Fuel Performance Code. Letter number BVY 89-74, Vermont Yankee Nuclear Power Corporation, Vermont.

10. Letter, M. B. Fairtile (NRC) to L. A. Tremblay (VYNPC). March 9, 1990. Subject: Request for Additional Information - FROSSTEY2 Fuel Performance Code (TAC No. 68216). U.S. Nuclear Regulatory Commission, Washington, D.C.

11. Letter, L. A. Tremblay (VYNPC) to Document Control Desk (NRC). April 19, 1990. Subject: Responses to Request for Additional Information on FROSSTEY2 Fuel Performance Code. Letter number BVY 90-045, Vermont Yankee Nuclear Power Corporation, Vermont.

12. Letter, L. A. Tremblay (VYNPC) to Document Control Desk (NRC). May 10, 1990. Subject: Supplemental Information to VYNPC April 19, 1990 Response Regarding FROSSTEY2 Fuel Performance Code. Letter number BVY 90-054, Vermont Yankee Nuclear Power Corporation, Vermont.

13. Letter, L. A. Tremblay (VYNPC) to Document Control Desk (NRC). March 6, 1991. Subject: Responses to Request for Additional Information on FROSSTEY2 Fuel Performance Code. Letter number BVY 91-024, Vermont Yankee Nuclear Power Corporation, Vermont.

14. Letter, C. E. Beyer (PNL) to S. L. Wu (NRC). August 19, 1991. Pacific Northwest Laboratory, Richland, Washington.

15. Letter, C. E. Beyer (PNL) to S. L. Wu (NRC). December 23, 1991. Pacific Northwest Laboratory, Richland, Washington.

16. Letter, L. A. Tremblay, Jr. (VYNPC) to Document Control Desk (NRC). March 27, 1992. Subject: LOCA-Related Responses to Open Issues on FROSSTEY2 Fuel Performance Code. Letter number BVY 92-39, Vermont Yankee Nuclear Power Corporation, Vermont.

17. Letter, L. A. Tremblay, Jr. (VYNPC) to Document Control Desk (NRC). May 15, 1992. Subject: FROSSTEY2 Fuel Performance Code - Vermont Yankee Response to Remaining Concerns. Letter number BVY 92-54, Vermont Yankee Nuclear Power Corporation, Vermont.

18. Cunningham, M. E., and C. E. Beyer. 1984. *GT2R2: An Updated Version of GAPCON-THERMAL-2.* NUREG/CR-3907 (PNL-5178), Pacific Northwest Laboratory, Richland, Washington.

19. Electric Power Research Institute. February 1987. *ESCORE - The EPRI Steady-State Core Reload Evaluator Code: General Description.* EPRI NP-5100 (Final Report), prepared by I. B. Fiero, Program Manager, Combustion Engineering, Inc., for the Electric Power Research Institute, San Jose, California.

20. Letter, A. C. Thadani (NRC) to C. R. Lehmann (PPLC). May 23, 1990. Subject: Acceptance for Referencing of Licensing Topical Report EPRI NP-5100. U.S. Nuclear Regulatory Commission, Washington, D.C.

21. Palmer, I. D., K. W. Hesketh, and P. A. Jackson. 1982. "A Model for Predicting the Radial Power Profile in a Fuel Pin." Presented at the IAEA Specialists Meeting on Water Reactor Fuel Element Performance Computer Modelling, Preston, United Kingdom.

22. Akerlund, S. O. et al. June 1, 1984. "The GESTR-LOCA and SAFER Models for the Evaluation of the Loss of the Loss of Coolant Accident - Volume 1: GESTR-LOCA - A Model for the Prediction of Fuel Rod Performance." NEDE-32785-1-P-A, Appendix B.

23. 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.