ENCLOSURE 2

MFN 16-025

"The PRIME Model for Transient Analysis of Fuel Rod Thermal – Mechanical Performance,"

NEDC-33840P, Revision 0, April 2016

Non-Proprietary Information – Class I (Public)

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Global Nuclear Fuel

NEDO-33840
Revision 0
April 2016

Non-Proprietary Information – Class I (Public)

THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD THERMAL-MECHANICAL PERFORMANCE

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ACRONYMS AND ABBREVIATIONS

Term	Definition
1D	One-Dimensional
3D	Three-Dimensional
AOO	Anticipated Operational Occurrence
BWR	Boiling Water Reactor
FGR	Fission Gas Release
FWCF	Feedwater Controller Failure
FWHM	Full Width Half Max
GE	General Electric
GNF	Global Nuclear Fuel
GNF-A	Global Nuclear Fuel – Americas, LLC
HBWR	Halden Boiling Heavy Water Reactor
ID	Inner Diameter
JMTR	Japan Materials Testing Reactor
L/D	Length/Diameter
LFWH	Loss of Feedwater Heater
LHGR	Linear Heat Generation Rate
LHGRFAC	Linear Heat Generation Rate Reduction Factor
LRNBP	Load Rejection with Bypass Failure
LTR	Licensing Topical Report
LWR	Light Water Reactor
MOP	Mechanical Overpower
MOP_{SS}^{SC}	Steady-State Mechanical Overpower Screening Criteria
[[	
	]]
ms	Milliseconds
NPD	Nodal Power Density
NRC	Nuclear Regulatory Commission
NSRR	Nuclear Safety Research Reactor
OD	Outer Diameter

Term	Definition
OP	Overpower
OPTRAN	Operational Transient
PBF	Power Burst Facility
PCMI	Pellet-Cladding Mechanical Interaction
PPE	Peak Pellet Exposure
PWR	Pressurized Water Reactor
RIA	Reactivity-Initiated Accident
RPD	Radial Power Distribution
RWE	Rod Withdrawal Error
SHF	Surface Heat Flux
SURT	Surface Temperature
TCL	Centerline Temperature
T-M	Thermal-Mechanical
TMOL	Thermal-Mechanical Operating Limits
TOP	Thermal Overpower
TOP_{SS}^{SC}	Steady-State Thermal Overpower Screening Criteria
[[	
	]]
US	United States
U95	Upper-95%
VAFT	Volume Average Fuel Temperature

1.0 INTRODUCTION

The PRIME model and methodology has been developed to provide fully integrated best-estimate predictions of fuel rod thermal and mechanical performance up to and beyond currently licensed burnup limits. The technical basis, qualification and application methodology for steady-state application, including steady-state (long duration relative to the fuel rod thermal time constant) transients, of PRIME are documented in previous licensing topical reports (LTRs) (Reference 1). The PRIME steady-state LTRs have been reviewed and approved by the United States (US) Nuclear Regulatory Commission (NRC). Subsequent to approval of the PRIME steady-state LTRs, the fast (short duration relative to the fuel rod thermal time constant) transient functionality of PRIME has been developed and qualified and a new application methodology specifically utilizing the transient functionality has been developed. The objectives of this LTR are to document the:

(1) technical basis of the PRIME analysis capability utilizing the transient functionality;
(2) experimental qualification of PRIME predictions of fuel cladding strains for transients utilizing the transient functionality, which includes reactivity-initiated accident (RIA) tests performed at the CABRI and Nuclear Safety Research Reactor (NSRR) test reactors, and operational transient (OPTRAN) tests conducted in the Power Burst Facility (PBF) test reactor; and
(3) application methodology of the PRIME transient analysis capability to commercial fuel rod behavior and licensing analyses.

Historically, fuel rod behavior analyses for steady-state operation and transients have been performed with separate codes. The main reasons behind this approach were the challenges associated with the development and implementation of a single code that was numerically capable of addressing both the steady-state and transient analyses regimes. Although workable, this approach can increase the prediction uncertainty due to interpolation between steady-state and transient response regimes and can increase the probability of error during transfer of key response variables between the separate codes. In addition, the identification of several key fuel performance issues resulting from the trend toward increased uranium utilization has created the need for advanced fuel rod modeling capability for both steady-state and transient response. Finally, due to the increasing expense and difficulty of in-reactor transient testing, a need exists for a code capable of transforming historical transient test results to current fuel designs and transient conditions and transforming transient test results performed for specific fuel designs and transient conditions to other designs and conditions.

To explicitly address these issues, the PRIME transient functionality has been developed and incorporated into the existing PRIME code to provide the option to perform fully integrated best-estimate predictions of fuel rod thermal and mechanical performance in both steady-state and transient operational regimes up to and beyond the currently licensed burnup limits. A typical transient application of PRIME will consist of a single analysis containing a steady-state portion representing operation prior to the transient event and used to determine fuel rod conditions at initialization of the transient event and a transient portion simulating the transient event of interest. The NRC previously reviewed and approved qualification and application of the

PRIME steady-state methodology, including application to steady-state (slow) anticipated operational transients (anticipated operational occurrences (AOOs)), as documented in Reference 1. Because the PRIME transient functionality is integrated into the previously approved PRIME code, some parts of the code are shared between steady-state and transient solutions. Therefore, in this LTR, reference to PRIME includes reference to both steady-state and transient functionality. If specification of either steady-state or transient functionality is necessary, it will be included as part of the reference to PRIME.

On the basis of this LTR, NRC approval is requested for application of the PRIME transient functionality and application methodology for licensing analyses of light water reactor (LWR) fuel rods for transient events within the approved peak pellet exposure (PPE) (or burnup) limits of the existing steady-state PRIME approval basis (Reference 1).

2.0 APPROACH

In the PRIME simulation of steady-state operation, including steady-state (slow) transients, the fuel and cladding radial temperature distributions at each axial node are determined by performing a one-dimensional (1D) time independent heat transfer analysis based upon the (thermal) conductivity integral methodology. For simulation of transient events in PRIME, the steady-state thermal solution is replaced with a transient thermal solution in which the radial temperature distributions in the fuel and cladding are determined by a transient heat transfer analysis. In the transient analysis, the spatial temperature response is obtained using the finite-difference technique. Small 1D radial elements are used to achieve accuracy and to capture the radial peaking of the fuel temperature distribution for high burnup fuel. The temperature response in the time domain is obtained using [[ ]]. Transient thermal results are fed into the PRIME fission gas model and mechanics model to solve for mechanics and material variables, including displacements, stresses and strains. The responses in the mechanics and material domains are obtained using the finite element technique. The PRIME mechanics model is unchanged, so with the exception of the transient temperature calculation and the use of smaller time steps, the program flow for PRIME steady-state and transient analyses is essentially identical. In both cases, mechanical coupling between axial nodes is addressed by an [[ ]], gas inventory coupling is addressed by assuming [[ ]] and an iterative process is used to assure consistency between the fission gas release (FGR) and the thermal and mechanical conditions at the end of each time step. The overall approach to implementation of the transient analysis functionality in PRIME is shown schematically in Figure 2-1.

As discussed, the PRIME transient functionality has been developed and incorporated into the existing PRIME code to provide the option to perform fully integrated fuel rod thermal and mechanical performance in both steady-state and transient operational regimes. This LTR is prepared as a single integrated LTR including Technical Basis, Qualification, and Application Methodology sections rather than three separate LTRs as in the case of the PRIME steady-state documentation.

The detailed technical basis of the PRIME transient functionality including program logic and limitations is provided in Section 3.0. The approach of this LTR is to address only the newly added transient functionality in detail. Therefore, models and sub-models that are the same for PRIME steady-state and transient analysis will not be repeated in this LTR; however, reference to the appropriate sections of the PRIME steady-state LTR addressing these model and sub-model details will be given. Validation and qualification of the PRIME transient analysis functionality is provided in Section 4.0. Experimental qualification results include comparisons of PRIME transient analysis predictions to measured fuel cladding (axial and diametral) deformations. The PRIME transient qualification database includes RIA tests performed at the CABRI and NSRR test reactors and OPTRAN tests conducted in the PBF test reactor. The methodology for application of PRIME for licensing and design applications to transient events is described in detail in Section 5.0.

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Figure 2-1. Overall Program Flow for Transient Analysis

3.0 TECHNICAL BASIS

This section provides descriptions of the technical bases for the PRIME component models, material properties relations, and descriptions of the overall structure of the PRIME model and implementation of the component models relative to the transient functionality.

3.1 Program Logic and Limitations

The PRIME (fast) transient functionality adds an option to PRIME to perform analyses of transient events which are short relative to the fuel rod thermal time constant. In terms of program logic, a transient temperature calculation has been added. For transient analysis, the PRIME steady-state temperature calculation is replaced by a transient temperature calculation. The overall PRIME steady-state program flow and the changes to the steady-state flow to incorporate the transient functionality are shown in Figure 3-1. The program logic and limitations are discussed below.

PRIME calculates fuel rod thermal and mechanical performance for variable operating power histories. The operating history can include both steady-state and transient portions. The fuel rod can be modeled by up to [[ ]]. The fuel rod operating power history is defined by the input of the irradiation conditions for a number of power-time (or exposure) steps. The transient portion of the history is identified by use of the input parameter IOPTR (i.e., IOPTR is set to 2 to activate the transient solution). The number of input time steps available to describe the power history is limited to a maximum of [[ ]] steps.

The input fuel rod operating power histories for steady-state and transient analyses are as shown in Figure 3-2. For both the steady-state and transient portions, PRIME performs combined incremental and iterative calculations. For the steady-state portion, the input power-time steps are [[

]]. Iterations are performed at each of these internal steps to determine gap conductance and pellet-clad interaction. The internal power and time increments have been set small enough to ensure convergence of the iterations. The nature of the fuel and cladding creep behavior requires small time steps after power changes when the creep rates may be high but permits larger time steps later in the analysis history when the creep rates are low. The time increments employed within a steady-state input time step have been parametrically derived to ensure accurate results over the expected range of stress-strain conditions and material properties of interest in the analysis of fuel rod operation. These analysis time increments are built-in and require the size of the input time step to be less than or equal to 2,000 hours. For the transient portion (those steps for which the PRIME input flag IOPTR is set to 2), the input power-time steps are internally divided into [[

]] The temperature solution is obtained by an iteration based finite-difference scheme within each internal step. After the temperature solution is obtained, iterations are performed for the internal step to determine gap conductance and pellet-clad interaction. These iterations are similar to those for the steady-state portion, but the flow is slightly different to accommodate the change in the clad temperature distribution during the temperature iterations.

PRIME performs coupled thermal and mechanical interaction analyses. The incremental finite element mechanics model performs an axisymmetric radial mechanical interaction analysis to determine pellet and cladding stresses and strains at the pellet mid-height location. For the steady-state portion of the power-time history, the thermal solution is obtained by numerical evaluation of the thermal conductivity integral. For the transient portion of the power history the thermal solution is obtained by iterative solution of finite-difference equations.

The sequence of calculations performed for analysis of a single power or time increment is shown in the program flow chart in Figure 3-1. First, the gas composition within the fuel rod is determined considering the initial fill gas and any fission gases released from the fuel during its irradiation history up to the present increment. An initial estimate of the fuel rod internal gas pressure is calculated based on the gas inventory, initial fuel rod void volume, and an assumed gas temperature. Next, the "axial nodes" loop is entered, wherein cladding temperatures are calculated from internally calculated cladding-to-coolant film coefficients (including the effects of input crud deposition and oxide formation on the cladding surface) and cladding thermal conductivity, or from user-specified values. This is followed by calculations to determine the extent of: (l) fuel irradiation-induced densification, causing pellet radial shrinkage away from the cladding; (2) fuel irradiation swelling, either filling pellet porosity or resulting in a positive expansion of the pellet; and (3) fuel cracking and relocation, resulting in radial displacement of the cracked pellet sections toward the cladding, reducing the diametral gap. For steady-state analysis, with an assumption for the hot fuel-cladding diametral gap, the "gap conductance" loop is entered, wherein an iterative procedure is employed to calculate the pellet surface temperature using a modified version of the gap heat transfer conductance model of Ross and Stoute (Reference 2). For steady-state analysis, after a converged pellet surface temperature and gap conductance are obtained for the assumed hot diametral gap, the fuel radial temperature distribution is calculated. The steady-state thermal model is described in detail in Reference 1. For transient analysis, with an initial assumption for the hot fuel-cladding diametral gap, the transient thermal solution is entered and the fuel pellet and clad radial temperature distribution is determined from finite-difference equations. The transient thermal model and solution are described in detail in Section 3.2.

These temperature distributions (in either steady-state or transient analyses) are used to determine the fuel and clad thermal expansion. After determination of the thermal expansion, the mechanical interaction calculations are performed. The sequence of mechanical interaction calculations is shown in the program flow chart in Figure 3-3. The radial thermal and mechanical calculations employ the idealization of concentrically located pellet and cladding. The radial effects of pellet eccentricity and/or tilting are addressed through modeling of the pellet-cladding gap closure. The axial effects of pellet eccentricity and/or tilting are addressed through the axial slip model. The axial slip algorithm predicts the relative fuel-cladding axial strain as a function of [[

]]. With this estimate of relative fuel-cladding axial strain, an initial estimate of the fuel and cladding total axial strain increment is made.

The simplified finite element radial mechanics analysis begins by separating the fuel rod into three cladding ring elements, one fuel-cladding gap element, and 10 fuel ring elements. The three cladding rings provide the capability to analyze non-barrier cladding, bimetallic (barrier) cladding consisting of an outer layer of Zircaloy and an inner layer of zirconium, and trimetallic cladding consisting of an outer layer of Zircaloy, an intermediate layer of zirconium, and an inner layer of Zircaloy (Triclad^{TM} cladding). When Triclad^{TM} fuel is analyzed, all three rings are used. When barrier fuel is analyzed, the thickness of the inner ring is set to zero. When non-barrier fuel is analyzed, the thicknesses of the two inner cladding ring elements are set to zero. The initial strain increments (treated as equivalent thermal strain increments) of each ring element due to swelling, densification, and thermal expansion are then determined. Depending upon whether the present analysis increment is a power step or a time step, either fuel and cladding plasticity calculations or fuel and cladding creep and pellet hot pressing calculations are performed. The resultant plastic or creep strain increments are then used, together with the crack front locations determined from the previous increment, in the determination of the fuel rod element load vectors. Determination and assembly of the fuel and cladding element stiffness matrices (involving an assumption on the state of the fuel-cladding gap (i.e., open or closed)), together with assembly of the element load vectors, then allows determination of the fuel and cladding ring element total strain increments. With the exception of changes in convergence criteria to accommodate differences in power and time increments, the PRIME mechanics model used in the transient solution is identical to the steady-state mechanics model (see Section 3.6).

The fuel and cladding stress components and axial loads are then determined. If the calculated fuel and cladding loads are not equal, another estimate of the fuel and cladding axial total strain increments is made and the calculations repeated until axial load equilibrium is established. At this point, the calculated fuel and cladding displacements are employed to update the fuel-cladding gap closure. If a converged thermal solution is also present at this time, the location of the fuel radial and transverse crack fronts are updated. If the thermal calculation is not converged, for steady-state analyses, an iterative calculation is performed to ensure consistency between the hot fuel-cladding diametral gap calculated by the mechanical model and the hot gap employed in the gap conductance calculation. For transient analyses, iterations are performed at each of the internal steps to ensure convergence of gap conductance and pellet-clad interaction. These iterations are similar to those for the steady-state portion, but the flow is slightly different to accommodate the change in the clad temperature distribution during the temperature iterations (See Figure 3-1). For either case, when convergence is obtained, the amount of fission gas released from the axial node can be determined.

After the conditions at each axial node have been calculated, the amount of nodal FGR is summed axially to allow a more accurate determination of the composition of the gas occupying the fuel rod void volume. With this more precise determination of the gas composition, the entire set of calculations is repeated. This single iteration on fuel rod internal gas composition is made for each power/time increment within the input power-time step. However, iterations to obtain complete convergence on the internal pressure are performed for the last power-time increment within the input power-time step.

For the PRIME transient solution, most fuel and cladding thermal-mechanical (T-M) behavioral models and material properties are unchanged from those used in the PRIME steady-state solution, as detailed in Sections 3.3 through 3.8. Any exceptions are noted in the detailed discussion in Sections 3.3 through 3.8. For models and properties which include explicit time dependencies, such as fuel densification, cladding creep and FGR, this approach is consistent with the current formulation of these models and material properties. For models and material properties which do not include explicit time dependencies, the approach implicitly assumes that the time dependencies of these models and properties are small relative to the fuel thermal time constant and that the responses of these models and properties to a change in power are essentially instantaneous relative to the time required for the corresponding change in temperature to occur.

In summary, the PRIME transient functionality shares most fuel and cladding T-M behavioral models and material properties with the PRIME steady-state functionality previously reviewed and approved by the NRC. Because fuel rod temperature calculations for transient events are not inherently different than for steady-state operation, provided that the fuel rod thermal time constant is correctly addressed, results of PRIME transient solutions for cases with long duration power changes and cases including fast power changes followed by constant power operation at the terminal powers are expected to be similar to results for the corresponding PRIME steady-state solutions, except immediately following the power changes, where the effect of the thermal time constant will result in lower temperatures. This anticipated response is confirmed in Section 4.1.2 for a subset of cases from the PRIME steady-state qualification.

PRIME is considered applicable for the T-M analysis of Zircaloy-clad uranium dioxide fuel rods in light or heavy water reactors. The fuel pellets may include additions of gadolinium dioxide or [[ ]] additives. The ranges of applicability for key dimensional and performance parameters are provided in Table 3-1. The limits of application are the same as those in the approved steady-state PRIME LTR (Reference 1) with the exception of cladding temperature for transient events. Approval for the cladding temperature limit for transient events is included as part of the request for approval for application to these events.

3.2 Transient Thermal Model and Solution

The PRIME transient temperature calculation assumes that [[

]] an appropriate clad to coolant heat transfer coefficient determined by transient thermal hydraulics methods can be input. Additionally, PRIME transient functionality allows for direct user input of cladding outer temperature.

The PRIME transient thermal analysis solution is based on [[

]]

In Equation 3-1, all the material properties are functions of temperature, which in turn is a function of radial position and time. Such nonlinearity makes it necessary to solve the transient heat transfer equation by numerical methods.

For the PRIME transient thermal solution, the finite-difference method is applied to address the spatial dependency in Equation 3-1. [[

]]. A typical geometry is shown in Figure 3-4. Discretization of the radial geometry is detailed in Figure 3-5.

The governing finite-difference equations are obtained by considering the energy balance on a defined system boundary as shown generically in Figure 3-6.

Each system boundary is defined by a corresponding nodal system derived from the discretization in the spatial dimension. In general, two or three nodes are considered for each discretized nodal system. General nodal systems with pertinent energy terms are detailed in Figure 3-7. By definition, consider energy in to be heat transferred from the adjacent node closest to the center of the fuel to the next node, and consider energy out to be heat transferred from the node of interest to the next node farther from the center. The rate of thermal energy generation is g and the rate of energy storage is $dE/d\theta$.

Based on the spatial discretization, [[ ]] energy balances are written, one for each nodal system. Making applicable substitutions into the energy balance gives the following governing ordinary differential equations which can be written for each corresponding nodal system:

[[

]]

The heat transfer into and out of the nodal system are represented by the appropriate rate equations, where the conduction rate equation is approximated based on finite-difference formulations:

[[

]]

The volumetric rate of thermal energy generation, g''', within the fuel pellet is determined as shown below in Equation 3-4. [[

]]

Writing the energy balance for each nodal system and applying the appropriate rate equations and material properties gives a system of [[ ]] simultaneous, first-order, ordinary differential equations of the forms given in Equations 3-2 and 3-3 (see Appendix A for the detailed derivation of each ordinary differential equation for each nodal system). The [[ ]] simultaneous, first-order, ordinary differential equations can be represented in matrix form as:

[[

]]

For PRIME transient analysis, the solution of the governing system of equations in the time domain is obtained using [[

]]. Models and material properties noted in this section or used in the transient thermal solution are described in Sections 3.2.1 through 3.2.7. Other models and material properties used in the transient solution are described in Sections 3.3 through 3.8.

3.2.1 Clad-to-Coolant Film Coefficient

Several options are available in PRIME for determining the clad-to-coolant film coefficient. For boiling conditions, the liquid film heat transfer coefficient is calculated using the Jens-Lottes equation (Reference 3). For conditions in which boiling does not occur and the coolant temperature increases as it traverses the fuel rod, the coolant temperature rise is calculated explicitly using a 1D energy balance, evaluated at each axial node. The coolant subchannel adjacent to the fuel rod is visualized as consisting of cells through which fluid may pass in the axial direction only. The liquid film heat transfer coefficient is calculated using the Dittus-Boelter equation (Reference 4). These options are unchanged from those discussed in detail in Section 3.1 of the PRIME steady-state LTR Part 1 (Reference 1).

In either option, the overall clad-to-coolant film coefficient is determined from the thermal resistances of the liquid film, crud layer and oxide layer. The thermal resistances of the oxide and crud layers are unchanged from those in Section 3.1 of the PRIME steady-state LTR Part 1 (Reference 1).

3.2.2 Pellet-Cladding Gap Conductance

The pellet-cladding gap conductance is calculated using a modified version of the Ross and Stoute model (Reference 2). The pellet-cladding gap conductance (h_g) is assumed to be comprised of three components: solid/solid contact conductance (h_s), conduction through the gas layer at the pellet-cladding interface (h_f), and conduction due to radiation heat transfer (h_r), that is,

$$h_g = h_s + h_f + h_r$$

This approach is unchanged from that discussed in detail in Section 3.2 of the PRIME steady-state LTR Part 1 (Reference 1).

3.2.3 Fuel Thermal Conductivity

The fuel thermal conductivity model used in PRIME transient analysis is unchanged from that described in Section 3.3.1 of the PRIME steady-state LTR Part 1 (Reference 1) and includes the effects of burnup, gadolinia and [[ ]] additive along with the effect of defect recovery due to thermal annealing.

The defect recovery model is as described in Section 3.3.1.2 of the PRIME steady-state LTR Part 1 (Reference 1) [[

]] As an example, a typical transient application of PRIME will consist of a single analysis containing a steady-state portion representing operation prior to the transient event and used to determine fuel rod conditions upon initialization of the transient event and a transient portion simulating the transient event of interest. [[

]]

3.2.4 Radial Power Distribution

Several radial power distribution (RPD) options are available for PRIME transient analysis. The RPD options are unchanged from those described in Section 3.3.2 of the PRIME steady-state LTR Part 1 (Reference 1).

3.2.5 Fuel Melting

The fuel melting temperature model used in PRIME transient analysis is unchanged from that described in Section 3.3.3 of the PRIME steady-state LTR Part 1 (Reference 1) and includes the effects of burnup.

3.2.6 Grain Growth

The grain growth model used in PRIME transient analysis is unchanged from that described in Section 3.3.4 of the PRIME steady-state LTR Part 1 (Reference 1).

3.2.7 Fuel Stored Energy

The fuel stored energy model used in PRIME transient analysis is unchanged from that described in Section 3.3.5 of the PRIME steady-state LTR Part 1 (Reference 1).

3.3 Material Properties

3.3.1 Cladding Elastic/Plastic Properties

The cladding elastic/plastic material properties used in PRIME transient analysis include Elastic Modulus, Poisson's Ratio, and Yield Stress and Hardening Rule and these are unchanged from those described in Section 4.1 of the PRIME steady-state LTR Part 1 (Reference 1).

3.3.2 Annealing of Clad Irradiation Hardening

The model for annealing of cladding irradiation hardening used in PRIME transient analysis is unchanged from that described in Section 4.2 of the PRIME steady-state LTR Part 1 (Reference 1).

3.3.3 Fuel Density

The fuel theoretical density calculated and used in PRIME transient analysis is unchanged from that described in Section 4.3 of the PRIME steady-state LTR Part 1 (Reference 1).

3.3.4 Fuel Elastic/Plastic Properties

The fuel elastic/plastic material properties used in PRIME transient analysis include Elastic Modulus, Poisson's Ratio, Yield Stress, Strain Hardening Coefficient and Tangent Modulus, and [[ ]]. These properties are unchanged from that described in Section 4.4 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4 Fuel and Cladding Expansion and Displacement Models

3.4.1 Fuel and Cladding Thermal Expansion

The fuel and cladding thermal expansion models used in PRIME transient analysis are unchanged from that described in Section 5.1 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.2 Cladding Irradiation Growth

The cladding irradiation growth model used in PRIME transient analysis is unchanged from that described in Section 5.2 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.3 Fuel Irradiation Swelling

The fuel irradiation swelling model used in PRIME transient analysis is unchanged from that described in Section 5.3 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.4 Fuel Densification

The fuel densification model used in PRIME transient analysis is unchanged from that described in Section 5.4 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.5 Fuel Relocation

The fuel relocation model used in PRIME transient analysis is unchanged from that described in Section 5.5 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.6 Cladding Creep

The cladding (and zirconium liner) creep models used in PRIME transient analysis are unchanged from that described in Section 5.6 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.7 Fuel Creep

The fuel creep model used in PRIME transient analysis is unchanged from that described in Section 5.7 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.8 Fuel Hot Pressing

The fuel hot pressing model used in PRIME transient analysis is unchanged from that described in Section 5.8 of the PRIME steady-state LTR Part 1 (Reference 1).

3.4.9 Fuel Cladding Axial Slip

The fuel cladding axial slip model used in PRIME transient analysis is unchanged from that described in Section 5.9 of the PRIME steady-state LTR Part 1 (Reference 1).

3.5 High Burnup Models

As described in Section 6 of the PRIME steady-state LTR Part 1 (Reference 1), most high burnup effects are addressed in PRIME by modifying material properties models or existing PRIME sub-models. A model to address the observed development of a porous pellet rim at high burnup is included in PRIME. The pellet rim model used in PRIME transient analysis is unchanged from that described is Section 6 of the PRIME steady-state LTR Part 1 (Reference 1). Material properties are described in other sections of this report.

3.6 Mechanics Model

In the mechanics solution, during the initial rise to power, fuel pellets develop radial and transverse cracks. These cracks initiate at very low power levels where the pellet temperatures are low and the pellets are brittle over their entire cross section. Consequently, these initial cracks most likely extend to the pellet centerline as a result of dynamic propagation. Subsequent power cycling results in intermittent radial and axial interaction between fuel and cladding. The radial interaction is primarily a result of differential expansion between pellet and cladding. The axial interaction is primarily a result of [[

]]

The mechanics solution, including description of mechanics models used in the solution, are described in detail in Section 7 of the PRIME steady-state LTR Part 1 (Reference 1).

The PRIME steady-state solution includes both material and sub-model explicit time dependencies. [[

]] With the exception of changes in convergence criteria to accommodate differences in power and time increments, the mechanics solution for PRIME transient analysis is unchanged from the mechanics solution for steady-state analysis.

3.7 Fission Gas Release Model

The FGR model options available for PRIME transient analysis are [[

]] and a user input option to specify the FGR at each time step. See Section 5.2 for details regarding application of the PRIME transient functionality.

3.8 Rod Internal Gas Pressure

The rod internal pressure calculation used in PRIME transient analysis is unchanged from the rod internal pressure calculation used in PRIME steady-state analysis as described in Section 9 of the PRIME steady-state LTR Part 1 (Reference 1). As discussed in Section 9, plenum temperature is used in the rod internal pressure calculation and is an input to each PRIME analysis. The plenum temperature is calculated as described in RAI-41 of the PRIME steady-state LTR Part 1 (Reference 1). Typically, the plenum temperature input for the steady-state portion of a PRIME analysis will also be applicable to the transient portion of a PRIME analysis, but a different value for the transient portion may be input to simulate specific transient events or conditions.

Table 3-1. Limits of Application – PRIME Transient Functionality

Parameter	Limit
[[	
	]]

[[

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Figure 3-1. Flow Chart for a Single Power or Time Increment

[[

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Figure 3-2. Input History and Analysis Schematic Representation

[[

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Figure 3-3. Flow Chart for Mechanics Model

[[

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Figure 3-4. Example Geometry

[[

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$r_p = fuel\ pellet\ radius$

$r_{ci} = clad\ inner\ radius$

$r_{co} = clad\ outer\ radius$

$\Delta r_p = fuel\ nodal\ spacing$

$\Delta r_b = zirconium\ barrier\ thickness$

$\Delta r_c = Zr - 2\ nodal\ spacing$

Figure 3-5. Discretization of Radial Geometry

[[

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Figure 3-6. General System Boundary

[[

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Figure 3-7. General Discretized Nodal Systems with Pertinent Energy Terms

4.0 VALIDATION AND QUALIFICATION

For the application of PRIME to transient events, the primary parameters of interest are the fuel centerline temperature (TCL) and the cladding diametral strain.

Measured fuel TCL data for fast transient events is not available. However, it is noted that fuel rod temperature calculations for transients are not inherently different than for steady-state operation provided that the effect of the fuel rod thermal time constant is correctly addressed. Measured cladding strain data for transient test programs is available. However, much of the data is from RIA test programs with only limited data from actual OPTRAN test programs representative of events, such as fast AOOs that occur in boiling water reactors (BWRs). It is acknowledged that RIAs can be very different from other transient events such as AOOs. RIAs typical of BWRs (and pressurized water reactors (PWRs)) are very rapid power pulses occurring with pulse full width at half-max of 10-100 milliseconds (ms), with essentially adiabatic heating of the fuel during the pulse. Fast AOOs are rapid power increases but with durations of approximately [[

]]

As previously discussed in Section 3.0, the PRIME transient functionality shares most fuel and cladding T-M behavioral models and material properties with the PRIME steady-state functionality. Also, as discussed above, fuel rod temperature calculations for transients are not inherently different than for steady-state operation provided that the effect of the fuel rod thermal time constant is correctly addressed. Therefore, good agreement of the results of PRIME transient solutions with the results of PRIME steady-state solutions for long duration power changes provides validation of the implementation of the transient functionality of PRIME. Thus comparison of the results of PRIME transient solutions to results of the PRIME steady-state solutions for existing steady-state qualification cases, including power changes, followed by constant power operation at the terminal powers, [[

]] As cladding strain measurements are available from transient tests, including RIAs and operational transients, code predictions of cladding strain are used directly for PRIME qualification for the calculation of cladding strain during transient events. Furthermore, GNF has found that [[

]]

A roadmap summarizing GNF validation and qualification of the PRIME transient functionality based on this discussion is provided in Figure 4-1.

4.1 Validation and Qualification of PRIME Transient Capability via Comparison to PRIME Steady-State Results

The intent of this section is to demonstrate that the overall approach is adequate to provide the desired transient functionality and to qualify the PRIME transient solution of temperature and cladding strain by comparison of PRIME transient results to PRIME steady-state results. This is done by comparing PRIME transient results for a hypothetical fast power ramp to PRIME steady-state results and by comparing PRIME transient results to PRIME steady-state results for steady-state qualification cases.

4.1.1 PRIME Transient vs PRIME Steady-State Solution for Hypothetical Transient Event

The PRIME transient solution and PRIME steady-state solution temperature and cladding diametral strain results are compared to confirm that the expected behaviors are observed (i.e., that the transient solution [[ ]]). For this comparison, the rod is assumed to operate at constant power of [[

]] as illustrated in Figure 4-2. The duration of the hold is sufficiently long relative to the fuel rod thermal time constant to achieve steady-state response. For the rod considered, the fuel rod thermal time constant, τ, depends upon the operating history, but is typically [[ ]].

The temperature and cladding strain results are shown in Figure 4-3. [[

]]. Both the transient temperature and strain responses are as expected, providing validation of the implementation of the transient solution in PRIME.

4.1.2 PRIME Transient vs PRIME Steady-State Solutions for Representative Steady-State Qualification Cases

The PRIME transient functionality implementation is based upon the assumption that most fuel and cladding T-M behavioral models and material properties are unchanged from those used in the PRIME steady-state solution as detailed in Section 3.0 (exceptions are noted in the detailed discussions in Sections 3.3 through 3.8). With this assumption, [[

]] Results of such comparisons are presented below.

[[

]]

4.2 Validation and Qualification of PRIME Transient Capability via Comparison to Results of Alternate Model and to Expected Behavior

The intent of this section is to demonstrate that the overall approach is adequate to provide the desired transient functionality and to qualify the PRIME transient functionality for prediction of temperature and cladding strain. This is done by comparing PRIME transient results for a typical operational transient to the results of analyses by an alternate code and assessing the PRIME responses relative to the expected responses for a typical RIA.

4.2.1 PRIME Transient Results for Typical Operational Transient

PRIME transient results for fuel TCL and VAFT are shown in Figure 4-20 for a typical feedwater controller failure (FWCF) transient event, together with corresponding results from alternative analyses using the finite element analysis code ANSYS. The FWCF transient event is an operational transient classified as an AOO. For this analysis, the transient event is assumed to initiate at an exposure of [[ ]], which is representative of the first knee (first change in slope) of typical GNF linear heat generation rate (LHGR) operating limits. The PRIME analysis is performed as a single analysis consisting of steady-state operation to initiation of the transient, followed by the transient. Fuel rod conditions at initiation of the transient are directly available from the steady-state results. The calculated fuel temperatures increase gradually from zero to 12 seconds, reflecting the gradual increase in power during the initial portion of the transient, then increase rapidly from 12 to 15 seconds during which time the power increases rapidly to approximately 4.5 and then to approximately 3.0 times the steady-state power. The calculated fuel temperatures then begin to decrease as the transient terminates. The calculated transient temperatures are significantly lower than the temperatures that would be calculated assuming steady-state response at the corresponding transient power. The transient response is as expected when the effect of thermal time constant is considered. Additionally, the ANSYS results are in excellent agreement with the PRIME transient results.

4.2.2 PRIME Transient Results for Typical RIA

[[ ]] RIA tests (details in Section 4.3.2) is used as an example of a typical RIA transient. The test fuel rod is a [[ ]] with base irradiation to [[ ]] pellet average exposure. The RIA full width half max (FWHM) test pulse width was [[ ]] and the peak enthalpy was [[ ]].

The power history during the RIA event is calculated from the [[ ]]. The resulting power is shown as a function of time in Figure 4-21. This figure illustrates the characteristics of an RIA transient event, namely the duration of the event is very short but the power increase is very large. The pulse is so short that heat-up during the pulse is approximately adiabatic (minimal heat transfer within the pellet or across the pellet-cladding gap). The calculated pellet surface temperature (Fuel SURT) and TCL are also shown in Figure 4-21. As shown, during the early portion of the RIA, the fuel surface temperature is higher than the fuel TCL due to adiabatic heat-up and radial power peaking at the pellet surface. As the RIA progresses, adiabatic heat-up and pellet thermal expansion result in increasing pellet-cladding gap conductance and decreasing pellet surface temperature. Although not shown in Figure 4-21, after the pulse conduction heat transfer would begin to reduce temperature for the entire pellet. Typical radial temperature distributions during the RIA are shown in Figure 4-22 at different times during the event; two before the peak power, one at peak power, and five after peak power. The results in Figure 4-21 confirm the observations about thermal response during an RIA. In summary, during the early portion of the RIA, the fuel is heated almost adiabatically and the fuel pellet temperature profile agrees closely with the RPD profile. As shown in Figure 4-23, due to the high burnup of the [[ ]] segment, the RPD is highly peaked at the pellet surface, and thus the temperature is peaked very close to the surface. As the RIA progresses, adiabatic heat-up and pellet thermal expansion result in increasing pellet-cladding gap conductance and decreasing pellet surface temperature. Subsequent to the power excursion, heat conduction eventually lowers temperatures for the entire pellet. The calculated thermal response for the RIA is as anticipated considering the duration of the event relative to the thermal time constant.

4.3 Validation and Qualification of PRIME Transient Capability via Comparison to Transient Qualification Database

The intent of this section is to use transient qualification data to demonstrate that the PRIME transient methodology is adequate to provide the desired transient functionality and to qualify the PRIME transient functionality for temperature and cladding strain analyses of transient events. Available PRIME transient qualification data consists primarily of: (1) operational transient data from the OPTRAN test program, and (2) RIA transient data from test programs conducted in the

NSRR and CABRI test reactors. The experimental transient data includes fuel enthalpy, fuel cladding diametral (hoop) and axial strains, FGR, and cladding outer surface temperature. The data was obtained during and/or after the transient. Each test program, including specific data used in this qualification, is summarized below.

4.3.1 Operational Transient Tests

OPTRAN tests (Reference 6) were conducted in the PBF test reactor in the US (Idaho) in 1984 with maximum local burnup up to 30 GWd/MTU. OPTRAN 1-1 tests (901-series test rods) simulated operational transients with reactor scrams. OPTRAN 1-2 tests (902-series test rods) were performed to evaluate the probability of fuel rod damage for the most severe BWR anticipated transient without scram. The test transients are similar to fast AOOs addressed in GNF fuel rod licensing. Fuel rods were General Electric (GE) production-like rods, except for fuel length and plenum volume (which was scaled to the fuel length). The fuel rods were base irradiated in a domestic commercial BWR. Measured FGR due to the transient is available for unfailed rods. [[

]]

4.3.2 RIA Tests

The NSRR test reactor in Japan has been running RIA tests for irradiated fuel rods since 1989. Tests have been performed on both BWR and PWR rod segments. References 7, 8, and 9 summarize tests on BWR fuel rods with maximum burnup up to 61 GWd/MTU. [[

]]

The CABRI test program (Reference 10) was performed in the CABRI test reactor in France from 1993 to 1998. The tests were performed for PWR fuel rod segments with maximum burnups up to 64 GWd/MTU. These tests were performed in a test loop in the CABRI test reactor with liquid sodium as the coolant at a temperature of 280°C. The natural pulse width (FWHM) for the CABRI test reactor is approximately 9.5 ms. [[

]]

4.3.3 Results for Transient Qualification Database

The PRIME transient qualification results are presented below. The comparison of predicted and measured cladding diametral (hoop) strains is shown in Figure 4-24. The plotted strains are the permanent cladding diametral strain changes due to the transient. [[

]] The comparison of predicted and measured cladding axial strains is shown in Figure 4-25. The axial strains are determined by comparing the rod lengths before the transients and at the time of measurement. In the figure, [[

]]

The comparisons of predicted and measured cladding diametral and axial strains for transients show that the transient results are generally unbiased over the ranges of strain and exposure included in the database. The results are also within the scatter of the corresponding steady-state cladding diametral and axial strain results presented in Reference 1. These steady-state results are included with the transient results in Figure 4-24 and Figure 4-25. As shown in these figures, the PRIME transient results are consistent with PRIME steady-state results. Because the major difference in the two functionalities is the treatment of transient thermal effects, and because validation of the correct implementation of the thermal transient is presented in Sections 4.1 and 4.2, [[

]] On this basis, GNF concludes that the PRIME transient functionality is adequate for application to analysis of transient events.

As discussed in Section 3.2, the PRIME transient solution is obtained using the [[

]]

Table 4-1. PRIME Transient Qualification Cases from OPTRAN Tests

Test No.	Test Year	Maximum Exposure (GWD/MTU)	Peak Fuel Power (kW/ft)
[[			
			]]

*Included in qualification.

Table 4-2. PRIME Transient Qualification Cases from NSRR Tests

Test No.	Test Date	Pulse Width (ms)	Maximum Exposure (GWd/MTU)	Peak Fuel Enthalpy (cal/g)	Failure Enthalpy (cal/g)
[[					
					]]

*Included in qualification.

Table 4-3. PRIME Transient Qualification Cases from the CABRI Program

Test No.	Test Date	Pulse width (ms)	Maximum Exposure (GWd/MTU)	Peak Fuel Enthalpy (cal/g)	Failure Enthalpy (cal/g)
[[					
					]]

*Included in qualification.

[[

]]

Figure 4-1. PRIME Transient Validation and Qualification Roadmap

[[

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Figure 4-2. Power History Used for Transient vs. Steady-State Temperature and Cladding Strain Comparison for a Hypothetical Transient Event

[[

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Figure 4-3. Transient vs. Steady-State Temperature and Cladding Strain Response for a Hypothetical Transient Event

[[

]]

Figure 4-4. Power History for [[ ]] **(at Bottom Thermocouple)**

[[

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Figure 4-5. Calculated Steady-State and Transient Centerline Temperatures [[

]]

[[

]]

Figure 4-6. (Average) Power History for [[ ]]

[[

]]

Figure 4-7. Calculated Steady-State and Transient Centerline Temperatures for [[
]]

[[

]]

Figure 4-8. Power History for [[ ]] (Peak Power Node)

[[

]]

Figure 4-9. Calculated Steady-State and Transient Cladding Permanent and Total Diametral Deformations for Ramp for [[ ]]

[[

]]

Figure 4-10. Calculated Steady-State and Transient Cladding Permanent Diametral Strains for Ramp for [[ ]]

[[

]]

Figure 4-11. Power History for [[ ]] **(Peak Power Node)**

[[

]]

Figure 4-12. Calculated Steady-State and Transient Cladding Permanent and Total Diametral Deformations for Ramp for [[ ]]

[[

]]

Figure 4-13. Calculated Steady-State and Transient Cladding Permanent Diametral Strains for Ramp for [[ ]]

[[

]]

Figure 4-14. Power History for [[ ]] **(Peak Power Node)**

[[

]]

Figure 4-15. Calculated Steady-State and Transient Cladding Permanent and Total Diametral Deformations for Ramp for [[ ]]

[[

]]

Figure 4-16. Calculated Steady-State and Transient Cladding Permanent Diametral Strains for Ramp for [[ ]]

[[

]]

Figure 4-17. Power History for [[ ]] (Node Corresponding to Maximum Measured Diametral Strain)

[[

]]

Figure 4-18. Calculated Steady-State and Transient Cladding Permanent and Total Diametral Deformations for Ramp for [[ ]]

[[

]]

Figure 4-19. Calculated Steady-State and Transient Cladding Permanent Diametral Strains for Ramp for [[ ]]

[[

]]

Figure 4-20. Example FWCF Fuel TCL and VAFT Evolution

[[

]]

Figure 4-21. [[ ]] Power, Fuel TCL, and Fuel Surface Temperature during RIA Event

[[

]]

Figure 4-22. Radial Temperature Distribution of [[ ]] **at Various Times during RIA Event**

[[

]]

Figure 4-23. RPD of [[ ]]

[[

]]

Figure 4-24. Predicted and Measured Cladding Diametral Strain for Both Transient and Steady-State (Ramp-Test) Qualification

[[

]]

Figure 4-25. Predicted and Measured Cladding Axial Strain for Both Transient and Steady-State (Ramp-Test) Qualification

5.0 APPLICATION

This section provides a description of the methodology for application of the PRIME transient functionality to the evaluation of transient events to confirm compliance to applicable GESTAR T-M acceptance criteria.

5.1 Summary of Methodology

For each GNF fuel design, thermal-mechanical operating limits (TMOL) are established based on GNF fuel rod T-M design and licensing methodology as described in Reference 1. The GNF fuel rod T-M design and licensing methodology ensures that the TMOL is established such that if each rod type is operated within its TMOL, all fuel T-M design and licensing acceptance criteria defined in GESTAR (Reference 11) are explicitly satisfied and fuel rod integrity is maintained throughout operation. Compliance to the GESTAR T-M criteria must be shown for both steady-state operation and (fast and slow) AOOs (i.e., events resulting in power excursions potentially above the steady-state LHGR operating limits). Therefore, the operating limits include both steady-state peak LHGR operating limits and allowable overpowers (OPs) above the steady-state peak LHGR operating limits defined to accommodate AOOs. Two GESTAR criteria are applicable to fuel rods subjected to transient events. These criteria limit fuel temperature (no fuel melting) and cladding strain during the event and are addressed in the GNF fuel rod T-M design and licensing methodology by the specification of an allowable thermal overpower (TOP) and an allowable mechanical overpower (MOP). The allowable TOP is specified to ensure that fuel rod failure due to fuel melting will not occur and is implemented as a no fuel melting criterion (i.e., $T_{fuel} < T_{melt}$). The allowable MOP is specified to ensure that fuel rod failure due to pellet-clad mechanical interaction will not occur and is implemented as a [[ ]] limit on cladding strain[1] [[ ]] during the event. See Figure 5-1 for a schematic of TOP and MOP. The derivation of allowable TOP and MOP include consideration of applicable uncertainties. Uncertainties are accounted for through a statistical approach in the case of TOP or a worst-tolerance approach in the case of MOP, which is consistent with Reference 1.

The concept of allowable TOP and MOP was developed to provide parameters that are easily evaluated using parameters available from nuclear analysis codes, such as LHGR or surface heat flux (SHF), and that can be used as conservative screening criteria during the core design process. Thus, allowable TOP and MOP may be thought of as screening criteria which are specified to conservatively ensure compliance with actual GESTAR acceptance criteria. The conservatism in the screening criteria is inherent in the application methodology used to develop

---

[1] [[

]]

them; this methodology includes accounting for modeling, design, and operational uncertainties such that compliance to actual GESTAR limits is confirmed on either statistical or worst tolerance basis. The relationships between TOP and MOP screening criteria and actual GESTAR acceptance criteria are shown schematically in Figure 5-2.

During the core design process, the response of the fuel to transient events, such as an AOO, is calculated by steady-state and/or transient nuclear codes, based on the event type analyzed. For events that are long in duration relative to the fuel rod thermal time constant[2] (i.e., slow transients), comparison of the results of steady-state nuclear codes (e.g., PANACEA) to the steady-state TOP and MOP screening criteria, denoted TOP_{SS}^{SC} and MOP_{SS}^{SC}, is performed to ensure compliance to GESTAR fuel temperature and cladding strain criteria. TOP_{SS}^{SC} and MOP_{SS}^{SC} are developed using the PRIME steady-state functionality and are defined relative to the (steady-state) LHGR operating limits; the methodology and resulting TMOL is shown schematically in Figure 5-3 and described in detail in the PRIME steady-state LTR Part 3 (Reference 1). For fast transient events, such as load rejection with bypass failure (LRNBP) and FWCF, the power excursion experienced during the transient can result in very high nodal power densities (NPDs) that typically occur over durations much less than the fuel rod thermal time constant. An example power trace for a fast AOO is shown in terms of NPD versus time in Figure 5-4; the length of a typical fuel rod time constant is shown for comparison. Comparing the results of transient nuclear codes (e.g., ODYN or TRACG) to steady-state OP screening criteria is overly conservative because the steady-state OP screening criteria are derived without accounting for the reduction in fuel rod temperature response for fast, short duration transients, because the steady-state OP screening criteria do not account for the effect of the fuel rod thermal time constant. Therefore, for fast transient events, compliance to GESTAR fuel pellet temperature and cladding strain acceptance criteria is based upon both the results of transient nuclear codes and PRIME transient analysis. There are three approaches in which PRIME transient functionality can be applied to demonstrate compliance to GESTAR acceptance criteria:

1. A detailed T-M transient analysis is performed with PRIME for the transient event of interest and the results are compared directly to fuel pellet temperature and cladding strain GESTAR acceptance criteria (described in Section 5.2.1.1);
2. A detailed T-M transient analysis is performed with PRIME and [[

   ]] (described in Section 5.2.1.2); or,

---

[2] The fuel rod time constant, τ, is dependent upon the fuel type and operating history, but is typically on the order of [[ ]] seconds. Thus the assumption that an event may be modeled as steady-state is appropriate when the time at the power level is longer than approximately [[ ]] seconds.

3. The results of transient nuclear codes are compared to [[ ]] (described in Section 5.2.2).

5.2 Application of PRIME Transient Functionality

The application of PRIME transient functionality typically includes a steady-state analysis portion, representing operation prior to the transient event used to determine fuel rod conditions at initialization of the transient event, and a transient analysis portion simulating the transient event of interest. The transient event power history is an input to the analysis obtained from GE (e.g., PANACEA, ODYN, or TRACG) or non-GE nuclear codes. [[ ]] The transient is initiated subsequent to a PRIME steady-state evaluation at multiple exposure points in the licensed exposure range. [[ ]] The three approaches summarized in Section 5.1, by which the PRIME transient functionality can be applied to demonstrate compliance to GESTAR acceptance criteria, are discussed in detailed below.

5.2.1 Detailed PRIME Transient Analysis

The first two approaches summarized in Section 5.1 involve detailed PRIME transient analysis. Detailed PRIME analysis refers to an analysis performed for a specific transient(s) to compare transient fuel temperature and cladding strain responses directly to fuel temperature and cladding strain limits or to compare [[ ]] Both of these approaches are discussed in this section.

5.2.1.1 Comparison to Fuel Temperature and Cladding Strain Limits

PRIME transient functionality can be applied to confirm compliance to GESTAR fuel temperature and cladding strain acceptance criteria by performing a detailed PRIME transient analysis to predict the fuel temperature and cladding strain responses during the specified transient event(s) and comparing these results directly to fuel temperature and cladding strain limits.

As noted, a PRIME transient analysis contains both a steady-state and transient portion which are collectively referred to as a PRIME transient analysis. The steady-state portion of a PRIME analysis represents operation prior to the transient event and determines fuel rod conditions at initiation of the transient. The transient portion of the PRIME analysis is initialized from the conditions determined from the steady-state portion with the applied transient power history simulating the transient event of interest. The PRIME transient analysis is performed by running PRIME in steady-state mode up to the specified exposure at which the transient response is to be evaluated, then the PRIME transient functionality is enabled and the response for the applied transient power history is analyzed. For each step in the PRIME analysis, centerline temperature and cladding strain are calculated.

In this case, the detailed PRIME transient analysis must account for uncertainties, because the PRIME predictions will be compared directly to fuel melting temperature and cladding strain GESTAR acceptance criteria. These uncertainties include modeling uncertainties, operational uncertainties, and manufacturing uncertainties. To account for these uncertainties, the same previously approved PRIME steady-state application methodology, documented in Reference 1, is applied. Nuclear codes and processes used to provide the power histories applied in PRIME transient analyses are separately approved and address other uncertainties, [[

]]

To demonstrate compliance to the fuel temperature criterion (no fuel melting), the transient analysis is performed statistically by applying the standard error propagation equation to the results of a PRIME transient best estimate (nominal) case and multiple single parameter perturbation analyses, as follows:

$$\sigma_{TCL}^2 = \sum_{i=1}^{n} \left[\frac{\partial T_{CL}}{\partial x_i}\right]^2 \sigma_{x_i}^2 + 2\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial T_{CL}}{\partial x_i}\frac{\partial T_{CL}}{\partial x_j}\sigma_{x_i}\sigma_{x_j}\rho_{x_i,x_j} \qquad \textbf{5-1}$$

where $\sigma_{TCL} = standard\ deviation\ of\ PRIME - T\ output\ fuel$
$centerline\ temerpature$

$i, j = indices\ for\ perturbation\ cases$

$n = total\ number\ of\ perturbatuon\ cases$

$x_i, x_j = input\ variables\ perturbed\ in\ the\ PRIME\ analysis$

$\frac{\partial T_{CL}}{\partial x_i}, \frac{\partial T_{CL}}{\partial x_j} = partial\ derivatives\ of\ PRIME\ output\ fuel\ centerline$
$temperature\ with\ respect\ to\ perturbed\ variables\ x_i, x_j$

$\sigma_{x_i}, \sigma_{x_j} = standard\ deviations\ of\ the\ perturbed\ PRIME\ input\ variable$

and $\rho_{x_i,x_j} = correlation\ coefficient\ for\ input\ variables\ x_i, x_j$

The evaluation of output parameter variances using the error propagation equation is performed as follows. A PRIME transient analysis is performed with all inputs at their best estimate values. This analysis establishes the best estimate (nominal) value of the PRIME transient predicted fuel TCL during the transient, $(T_{CL})_{NOM}$. Additional PRIME transient analyses are then performed with each input variable (x_i) individually perturbed S standard deviations from its best estimate value in the direction that worsens the fuel temperature results, resulting in the parameter $(T_{CL})_{PERTURBED}$. The results from these perturbation analyses are then utilized with the best estimate results to calculate finite-difference approximations of the partial derivatives as follows for use in the error propagation equation:

$$\frac{\partial T_{CL}}{\partial x_i} = \frac{(T_{CL})_{PERTURBED} - (T_{CL})_{NOM}}{S\sigma_{x_i}} \quad \textbf{5-2}$$

The PRIME transient fuel TCL variance is then calculated using the standard error propagation equation, Equation 5-2.

The upper-95% (U95) confidence value for the PRIME transient predicted fuel TCL is then given by:

$$(T_{CL})_{U95} = (T_{CL})_{NOM} + 1.645\sigma_{TCL} \quad \textbf{5-3}$$

where 1.645 is the 95% confidence statistical tolerance factor.

The specific statistical perturbations performed include:

[[

]]

The U95 fuel TCL during the transient is then compared directly to the fuel melting temperature to ensure that fuel melting does not occur.

To demonstrate compliance to cladding strain criteria, a worst-tolerance approach is used in which all design and operating parameters that affect calculated cladding strain are placed at their worst tolerance limit. The specific parameters perturbed in the worst tolerance approach include:

[[

]]

The resultant [[ ]] strain using the worst tolerance approach during the transient is then compared directly to the appropriate cladding strain limit to ensure that the limit is met.

The fuel temperature and cladding strain analyses are performed [[ ]] to ensure GESTAR T-M acceptance criteria are met for the licensed exposure range.

An example FWCF case has been analyzed at approximately the 1st knee exposure point of typical LHGR operating limits for an example UO_2 rod using this methodology. The power history analyzed for this PRIME transient analysis example is shown in Figure 5-5, illustrating both the steady-state and transient portion. The results of the PRIME transient analysis are shown in Figure 5-6. Both the nominal (best-estimate) and U95 TCL and nominal and worst tolerance incremental cladding strain [[ ]] are shown at each time step in the transient power history; the GESTAR fuel melting temperature and cladding strain acceptance criteria at the analyzed exposure are also shown. The maximum U95 TCL and maximum worst tolerance [[ ]] cladding strain are compared directly to the GESTAR acceptance criteria to confirm compliance with fuel temperature and cladding strain acceptance criteria.

5.2.1.2 Comparison to [[ ]]

PRIME transient functionality can be applied to confirm compliance to GESTAR fuel temperature and cladding strain acceptance criteria by performing a detailed PRIME transient analysis to predict the fuel temperature and cladding strain response during the specified transient event(s) and [[

]]

A detailed PRIME analysis is performed identical to that described in Section 5.2.1.1, consisting of both a steady-state portion and a transient portion for the specified transient event(s) of interest. As before, the transient power history is input to the analysis and centerline temperature and cladding strain are calculated by PRIME. From these results, the maximum TCL and

[[ ]] strain predicted during the transient event are determined. The maximum TCL and [[ ]] strain values predicted during the transient event are then [[ ]]

The methodology for determining the [[ ]] The outline of this method is illustrated in Figure 5-7.

The derived [[ ]] as illustrated in Figure 5-8.

The analysis is performed [[ ]] to ensure GESTAR T-M acceptance criteria are met for the licensed exposure range. As noted, [[

---

[3] [[ ]]

]]

An example FWCF case has been analyzed (same as in Section 5.2.1.1) at the 1st knee exposure point of typical LHGR operating limits for an example UO_2 rod using this approach. The results are shown in Figure 5-9. For illustration purposes, [[ ]] are shown throughout the transient power history; the applicable [[ ]] to confirm compliance with GESTAR fuel temperature and cladding strain acceptance criteria.

5.2.2 **Development and Application of** [[ ]]

The third approach summarized in Section 5.1 involves applying PRIME transient functionality to determine [[ ]]

To determine [[ ]] first the fuel rod response parameter of interest [[ ]] by running detailed PRIME transient analyses as described earlier in Sections 5.2.1.1 and 5.2.1.2. This response parameter is [[ ]] The method of developing [[ ]] is shown schematically in Figure 5-10. As previously described, typically the [[ ]] is used to illustrate the methodology in Figure 5-10. In Figure 5-10, the [[ ]] This is illustrated schematically in Figure 5-10, in which the [[

]]

The analysis is performed [[ ]] to ensure GESTAR T-M acceptance criteria are met for the licensed exposure range. The PRIME transient analyses are performed [[

]]

In the event that the [[

]]

5.2.2.1 Representative Transients [[
]]

As discussed above, [[

]]

5.3 Assessment of Application of PRIME Uncertainty in Transient Analysis

As discussed above, GNF intends to apply the PRIME transient analysis capability to licensing analyses of transient events. Specifically, PRIME transient functionality will be used to confirm that GESTAR fuel temperature and cladding strain acceptance criteria are satisfied for transient events by (1) comparing PRIME transient predictions of fuel temperature and cladding strain directly to corresponding GESTAR acceptance criteria, (2) by comparing [[

]] which ensure compliance with the GESTAR acceptance criteria.

If PRIME temperature and cladding strain results during a transient are compared directly to GESTAR acceptance criteria, PRIME analyses of the transient events are performed to account for uncertainties as described in Section 5.2.1.1. That is, for fuel temperature calculations, the U95 fuel temperature is derived based on a statistical approach and for cladding strain calculations, the cladding strain is derived on a worst tolerance basis. [[

]] For these reasons and other reasons discussed in Section 4.0, GNF concludes that for analyses that use TOP screening criteria or fuel temperature directly, the PRIME steady-state statistical analysis methodology remains applicable for transient analyses. Similarly, GNF concludes that for analyses that use MOP screening criteria or cladding strain directly, the PRIME steady-state worst tolerance methodology remains applicable for transient analyses. Figure 5-11 presents worst tolerance results for the transient diametral strain qualification cases from Section 4.0. The worst tolerance results were obtained per the methodology described in Section 5.2.1.1. Figure 5-11 also includes worst tolerance results for the PRIME steady-state ramp test qualification data. [[

]] Thus, the results in Figure 5-11 confirm that the worst tolerance methodology approved for steady-state licensing is adequate for prediction of cladding strain for transient licensing analyses. If screening criteria are used to confirm compliance to GESTAR acceptance criteria, PRIME analyses of the transient events are performed on a best-estimate basis because the screening criteria are developed by accounting for uncertainties using the approved PRIME steady-state application methodology.

[[

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Figure 5-1. Schematic of Thermal and Mechanical Overpowers

[[

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Figure 5-2. Relationship Between TMOL (LHGR), Steady-State TOP and MOP Screening Criteria, and GESTAR T-M Limits for Fuel Melting and Cladding Strain

[[

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Figure 5-3. Example Steady-State TMOL Development (Schematic)

[[

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Figure 5-4. Example Transient Power Trace and Typical Fuel Thermal Time Constant

[[

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Figure 5-5. Example PRIME Transient Analysis Power History (Typical FWCF)

[[

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Figure 5-6. Example FWCF Fuel TCL and [[ ]] Cladding Strain Evolution

[[

]]

Figure 5-7. Determination of [[ ]] Overpower Response

[[

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Figure 5-8. Relationship Between Best-Estimate Fuel Rod Response and Fuel Rod Response Associated with Steady-State TOP and MOP Screening Criteria

[[

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Figure 5-9. Example FWCF [[ ]] Evolution

[[

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Figure 5-10. Determination of [[ ]]

[[

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Figure 5-11. Predicted (WSTOL) Cladding Diametral Strain for Transient Qualification and Predicted (WSTOL) Cladding Diametral Strain for Steady-State Ramp Test Qualification Data versus Measured Diametral Strain

6.0 SUMMARY

This LTR documents the incorporation of a transient analysis capability into the PRIME code. The PRIME transient functionality has been developed and incorporated into the existing PRIME code to provide the option to perform predictions of fuel rod thermal and mechanical performance in both steady-state and transient operational regimes up to and beyond the currently licensed burnup limits.

PRIME addresses the effects of fuel/cladding thermal expansion, fuel phase change volume change, fuel irradiation swelling, densification, relocation and FGR, fuel-cladding axial slip, cladding creepdown, irradiation hardening and thermal annealing of irradiation hardening, pellet and cladding plasticity and creep, pellet hot pressing and plastic collapse, and development of a porous pellet rim at high exposure. PRIME performs coupled thermal and mechanical interaction analyses. The incremental finite element mechanics model performs an axisymmetric radial mechanical interaction analysis to determine pellet and cladding stresses and strains at the pellet mid-height location. The mechanical effect of fuel column/cladding axial interaction is explicitly addressed in this analysis. The PRIME steady-state thermal solution is obtained by numerical evaluation of the thermal conductivity integral and the PRIME transient thermal solution is obtained by a transient thermal solution in which the radial temperature distributions in the fuel and cladding are determined using the finite-difference technique. Details of the technical basis for PRIME transient analysis are provided in Section 3.0.

The intent of this LTR is to support NRC approval of the application of the PRIME transient functionality to licensing analyses of transient events. Measured fuel temperature data for fast transient events is not available to directly qualify PRIME temperature predictions for fast transients. However, because fuel temperature is primarily a function of power, if the effect of thermal time constant is adequately addressed in the PRIME transient thermal solution, [[

]] The other validation results discussed in Section 4.3 further confirm that the effect of the fuel time constant is adequately addressed. Specifically, quantitative comparison of PRIME results to diametral and axial cladding strain measurements from transient tests confirms that PRIME predicts these strains well on a best-estimate basis for both operational transients and RIA tests, considering the uncertainties in the measurement techniques and assumed initial conditions. On the basis of the above, GNF concludes that PRIME adequately predicts temperatures and cladding strains for transient events.

It is GNF's intent that upon approval of this LTR, the PRIME transient functionality documented in the LTR will be applied within the approved PPE (or burnup) limits of the existing PRIME code approval basis to confirm compliance to GESTAR fuel temperature and cladding strain acceptance criteria. As described in Section 5.0, there are three approaches by which PRIME transient functionality can be used to confirm that the GESTAR acceptance criteria are satisfied. In the first approach, the PRIME transient functionality is applied directly to a specific event to confirm compliance to applicable GESTAR acceptance criteria by comparison of the maximum fuel temperature and cladding strain increment experienced during the transient directly to the corresponding GESTAR acceptance criteria. In the second approach, the PRIME transient functionality is applied directly to a specific event to confirm compliance to applicable GESTAR acceptance criteria [[ ]] In the third approach, the PRIME transient functionality is used to develop [[ ]] If PRIME temperature and cladding strain results are compared directly to GESTAR acceptance criteria, PRIME analyses of the transient events are performed using the approved PRIME steady-state application methodology to account for uncertainties (i.e., for fuel temperature calculations the U95 fuel temperature is calculated and for cladding strain calculations the worst tolerance strain is calculated). The adequacy of the U95 statistical approach for fuel temperature calculations and worst tolerance methodology for cladding strain calculations for transient events is confirmed in Section 5.3.

7.0 REFERENCES

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APPENDIX A - TRANSIENT THERMAL SOLUTION

Derivation of the governing first-order, ordinary differential equations for the [[ ]] nodal systems used in the PRIME finite-difference thermal solution are presented below.

A.1 First Node of Fuel Region (Hollow Pellets)

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Figure A-1. Schematic of 1st Node of Hollow Fuel Region

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A-1

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A.2 First Node of Fuel Region (Solid Pellets)

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Figure A-2. Schematic of 1st Node of Solid Fuel Region

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A-6

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A.3 Interior Nodes of Fuel Region

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Figure A-3. Schematic of Fuel Interior Node

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A.4 Outer Surface Node of Fuel Region

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Figure A-4. Schematic of Fuel Surface Node

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A.5 Inner Surface Node of Clad

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Figure A-5. Schematic of Clad Inner Surface Node

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A.6 Zircaloy-2/Zirconium Barrier Interface Node of Clad

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Figure A-6. Schematic of Zircaloy-2/Zirconium Barrier Interface Node

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A-11

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A.7 Zircaloy-2 Interior Node of Clad

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Figure A-7. Schematic of Zircaloy-2 Interior Node

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A-12

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A.8 Outer Surface Node of Clad

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Figure A-8. Schematic of Zircaloy-2 Outer Surface Node

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