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Licensing Topical Report

IMPLEMENTATION OF PRIME MODELS AND DATA IN DOWNSTREAM METHODS

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Abstract

The approval of the PRIME thermal-mechanical methodology requires the implementation of consistent fuel property models in codes supporting downstream analyses, such as ECCS/LOCA, stability, and transients . This Licensing Topical Report identifies the scope of these changes, the expected implementation strategy, the minimum validation requirements, and the actions necessary for subsequent review.

1.0 INTRODUCTION

1.1 OVERVIEW

The PRIME[1],[2],[3] model and computer program have been developed to provide predictions of the thermal and mechanical performance of (U,Gd)O_2 light water reactor nuclear fuel rods experiencing variable power histories. The PRIME code has been developed from the GESTR-Mechanical (GSTRM)[4] code, primarily to enhance modeling for high exposures and to update modeling for more recent experimental data. Some downstream safety analysis codes incorporate simplified fuel property models that comprise a subset of the type found in PRIME. The two most important of these models, for purposes of downstream safety analyses, are fuel thermal conductivity and fuel pellet to cladding gap conductance. PRIME incorporates a significantly enhanced model for the fuel pellet thermal conductivity. The PRIME pellet-clad gap conductance model formulation has only changed slightly. However, the PRIME code calculated gap conductance will be different from GSTRM due to other models that provide inputs and boundary conditions. This document contains a general plan for incorporation of PRIME-based properties into Engineering Computer Programs (ECPs) and methodologies as described in GESTAR-II-US[5]. The following codes are definitely impacted by this change: SAFER, CORCL, ODYSY, ODYN, and TASC. The generic code names, and specific versions to be updated, are summarized in Table 1-1. Additionally, the steady state nuclear methods will be evaluated for impact as described in Sections 2.2 and 3.3.1.

The changes required for each code are given in more detail in Section 2. The general process for controlling, testing, and releasing updated versions of the ECPs is provided in Section 3.

Table 1-1. Impacted ECPs Using Pre-PRIME Fuel Properties

Methodology	Engineering Computer Program	Reference
Transients	ODYN (ODYNM10A, ODYNV09A)	[6], [7], [8], [9], [10], [11]
	TASC (TASC-03A)	[12], [13], [14]
Stability	ODYSY (ODYSY05A)	[15], [16]
LOCA/ECCS	SAFER (SAFER04A)	[17], [18], [19], [20], [21], [22], [23], [24]
	CORCL (CORCL07A)	[20], [21], [25]
	TASC (TASC-03A)	[14]

1.2 GENERIC IMPLEMENTATION APPROACH

The ECPs to be modified for consistency with PRIME are given in Table 1-1. These are the current production-level ECPs that utilize pre-PRIME fuel properties in the associated calculations. The ECPs primarily incorporate fuel property models for purposes of calculating fuel/cladding temperature and fuel rod surface heat flux. The controlling fuel properties for these calculations are fuel thermal conductivity and fuel-clad gap conductance. Other ECP fuel properties, such as theoretical density and specific heat capacity, will be checked for consistency with PRIME in conjunction with the thermal conductivity model implementation.

These ECPs use a variety of methods for calculating fuel thermal conductivity and gap conductance. The approaches for fuel thermal conductivity vary from a simplified function of temperature to a function of temperature, gadolinia concentration, exposure, and fraction of theoretical density. The approaches for gap conductance vary from a single core-averaged constant value to a dynamic gap conductance calculation, as a function of local linear heat generation rate and exposure and initialized by a GSTRM or PRIME calculation.

The PRIME ECP subroutine that calculates fuel thermal conductivity is a function of temperature, exposure, gadolinia concentration, additive concentration, plutonium concentration, fraction of theoretical density, and fuel melting temperature. This subroutine will be encapsulated with a simplified interface so that ECPs need only provide temperature, exposure, gadolinia concentration, additive concentration, and fraction of theoretical density. The primary adaptation of this model relative to the PRIME code is that instantaneous fuel temperature will be used in any calculation for which PRIME uses history weighted temperatures. Note that a Plutonium concentration of 0.0 % will be assumed for the simplified interface.

The PRIME model for pellet-clad gap conductance requires input from other fuel thermal-mechanical models not typically available in safety analysis ECPs. Gap conductance output from PRIME will be used as input to other ECPs, rather than attempting to replicate the PRIME gap conductance model in each ECP. This output will either be gap conductance values, or files used to initialize ECPs with dynamic gap conductance models (SAFER and TRACG).

Additional inputs will be made available to allow selection of PRIME-based fuel thermal conductivity, and to provide additional arguments to the fuel thermal conductivity calculation. PRIME-based gap conductance will be selected by input of a PRIME-calculated gap conductance or dynamic gap conductance initialization files.

Although the PRIME fuel thermal conductivity formulation is a function of more parameters than previously required, additional detail will not be added to the ECP structure. For example, ODYN utilizes a single one-dimensional (axial) fuel rod. This will not be changed. However, inputs may be provided to allow for axially varying core averaged exposure, gadolinia concentration, and additive concentration. No ECP changes will be made to accommodate PRIME-based gap conductance. This will be handled exclusively through existing inputs.

2.0 METHODOLOGY CHANGES

Each section will contain a brief description of the methodology, current degrees of freedom, and style of implementation for incorporating PRIME thermal properties.

2.1 FUEL THERMAL MECHANICAL

The PRIME03P computer program is used to calculate the thermal/mechanical response of nuclear fuel to time varying power histories. Calculated response parameters include fuel centerline temperature, fission gas release, rod internal pressure, and cladding stress, strain and deformation (including local stress, strain, and ridge height). PRIME can be used for steady state licensing analysis of UO_2 and $(U,Gd)O_2$ fuel with (and without) additive material. Since PRIME contains thermal property formulations of thermal conductivity and gap conductance, consistency with downstream applications is desired. Establishing a licensing basis for fuel additive is not the purpose of this licensing topical report.

2.2 STEADY STATE NUCLEAR METHODS

The "Improved Steady-State Methods"[26], also known as TGBLA06/PANAC11, are used for core design, licensing, and core monitoring. PANAC11 leverages the TGBLA06 Level 2 ECP for preparation of homogenized nodal constants. TGBLA06 is a lattice design computer program for conventional BWRs that have lattices based on 8x8, 9x9, or 10x10 rod matrices. The lattice physics ECP TGBLA06 is not affected by the PRIME thermal property formulation.

The steady-state nuclear methods (PANAC11) require all fission and gamma energy generated in the fuel to be directly deposited in the fuel or moderator. It does not solve the pin conduction equation so there is no direct dependence on thermal-conductivity and/or gap conductance. Instead, it implements a relationship between thermal power and fuel temperature for Doppler feedback. Because Doppler feedback is not a strong reactivity contributor at steady-state conditions in a boiling water reactor environment, there is no strong feedback when changing to PRIME from GSTRM. Currently, the formulation is dependent only on significant changes in product line (8x8, 9x9, and 10x10) and is not dependent on exposure. This lack of dependency on exposure is not directly associated with the thermal conductivity formulation but a reasonable assumption for steady-state applications.

However, an investigation on the difference between PRIME based heat flux tables and the existing GSTRM based heat flux tables will be completed. If the PRIME relationship is statistically significantly different, the PANAC11 input structure will be modified and the fuel temperature calculation will allow usage of this new structure as an option. In the event that changes to PANAC11 are required, codes downstream of PANAC11 may need modification, depending on the particular form of the changes to PANAC11.

PANAC11 retrieves some thermal-hydraulic information from a steady-state ECP denoted as ISCOR. ISCOR is not directly dependent on thermal-mechanical properties since the heat flux on the rods is a direct input to the steady-state thermal-hydraulics simulation.

2.3 TRANSIENT ANALYSIS

Various plant transients are analyzed for purposes of plant and core licensing. The transient analyses of various anticipated operational occurrences are used for reload licensing and operating limit determination. In particular, system pressure, reactor vessel level, fuel minimum critical power ratio (MCPR), and fuel thermal-mechanical response may be evaluated for acceptability. For the present purposes, the anticipated transients without scram are also included with the transient analyses since the same ECPs are impacted. The rod withdrawal error and loss of feedwater heating events are normally analyzed with PANACEA (see Section 2.2). The bulk of transient events are analyzed with ODYN using one-dimensional kinetics. When ODYN is utilized, the nuclear data is extracted and collapsed from PANACEA by a buffer code and the MCPR post-processing is performed by TASC.

2.3.1 ODYN

The ODYN ECPs use a single core average gap conductance value, with optional axial multipliers. This will continue to be the case, although the source of these inputs will be based on PRIME.

The current fuel thermal conductivity formulation in ODYN is a built-in table of thermal conductivity as a function of temperature. The only user input is a global multiplier on fuel/clad thermal conductivity. ODYN will be modified with a switch to select the PRIME-based fuel thermal conductivity. With this option selected, ODYN will use the PRIME-based thermal conductivity as a function of temperature, exposure, gadolinia concentration, additive concentration, and fraction of theoretical density. These additional arguments will either be provided from PANACEA through the buffer code, supplied as default values, or supplied by the user.

2.3.2 TASC

The TASC ECP has multiple gap conductance options. However, constant, axially-varying values are typically input. This input may change to be consistent with PRIME.

The current TASC fuel thermal conductivity formulation is also a function only of temperature, although the table can be overlayed by the user. TASC will be modified to employ a similar strategy as ODYN for the PRIME-based fuel thermal conductivity calculation.

2.4 STABILITY

Core and channel decay ratio calculations are performed to ensure that the fuel is as stable as previously licensed GE fuel designs, or to revise the stability exclusion region.

Additionally, CPR response calculations are performed to demonstrate that the generic DIVOM curve (Delta CPR over Initial CPR Vs. Oscillation Magnitude) is applicable, or to generate a new curve. Finally, stability events are simulated to confirm the adequacy of detect and suppress solutions. Frequency-domain stability calculations are performed with the ODYSY ECP and time-domain stability calculations are performed with TRACG (see Section 2.6).

The ODYSY ECP allows the input of gap conductance for up to each axial level of each channel group. Typically, however, a core average value with simple power dependence is utilized. Only the supplied input will change for the PRIME-based gap conductance implementation.

Currently, ODYSY can calculate the fuel thermal conductivity as a function of temperature and gadolinia concentration. ODYSY will be modified with a switch to select the PRIME-based fuel thermal conductivity. With this option selected, ODYSY will use the PRIME-based thermal conductivity as a function of temperature, exposure, gadolinia concentration, additive concentration, and fraction of theoretical density. These additional arguments will either be provided from PANACEA through the buffer code, supplied as default values, or supplied by the user.

2.5 LOCA/ECCS PERFORMANCE

The SAFER/GESTR methodology is currently used to determine the effects of the loss–of–coolant accident (LOCA) in accordance with the requirements of 10CFR50.46 and Appendix K. This methodology utilizes ECCS evaluation models along with a realistic application approach to calculate a licensing peak clad temperature (PCT) with margin substantiated by statistical considerations. This methodology involves the SAFER, CORCL, and TASC ECPs (see Section 2.3.2 regarding TASC).

2.5.1 SAFER

The SAFER ECP has the option to use input gap conductance values for each heated node of each rod group, or use the built-in gap conductance model (constant or dynamic). Normally, the dynamic gap conductance model is used, requiring the input of initialization data from GESTR or PRIME. Only the supplied input will change for the PRIME-based gap conductance implementation.

SAFER currently allows for the input of fuel thermal conductivity as a function of temperature. SAFER will be modified with an option to select the PRIME-based fuel thermal conductivity as a function of temperature, exposure, gadolinia concentration, additive concentration, and fraction of theoretical density.

2.5.2 CORCL

The CORCL ECP has similar gap conductance options as SAFER. Normally, the required information is passed to CORCL from SAFER via interface files. No code changes will be made to CORCL to implement the PRIME-based gap conductance.

CORCL currently allows for fuel thermal conductivity as a function of temperature to be passed from SAFER, based on an internal model, or input by the user. CORCL will be modified with an option to select the PRIME-based fuel thermal conductivity as a function of temperature, exposure, gadolinia concentration, additive concentration, and fraction of theoretical density.

2.6 TRACG

The TRACG04A,P ECP may be used for multiple applications, including transients[27],[28],[29],[30], stability[31],[32], and, in the future, ECCS/LOCA (TRACG04 has been used for ESBWR LOCA calculations[33], with an application for other plants under development). TRACG is discussed separately since it has been recently extensively reviewed, and will not be modified for the PRIME implementation.

TRACG has the option to use input gap conductance values for each heated node of each rod group of each CHAN component, or use the built-in gap conductance model (constant or dynamic). Normally, the dynamic gap conductance model is used with TRACG, requiring the input of initialization data from GESTR or PRIME. Only the supplied input will change for the PRIME-based gap conductance implementation.

The current TRACG default fuel thermal conductivity formulation is essentially the PRIME-based formulation without additive. In particular, the thermal conductivity is a function of temperature, exposure, gadolinia concentration, and fraction of theoretical density. With 3D kinetics, the exposures are automatically set to the values from the PANAC wrapup used for the steady state calculation. Gadolinia concentration currently defaults to 0.0 and fraction of theoretical density currently defaults to 0.97, although these values may be changed by input.

3.0 IMPLEMENTATION AND TESTING

3.1 SOFTWARE QUALITY ASSURANCE PLAN

GEH follows a quality assurance (QA) plan for ECPs that is compliant with Appendix B of Title 10 Part 50 of the Code of Federal Regulations (10 CFR 50). In accordance with this procedure, the code changes described within this document will be classified as a maintenance activity since the original constructions based upon GSTRM formulations and application will still be available. The software test plan and software test report will be constructed to test all changes made to the ECPs as well as sufficient testing to provide confidence that other models or functionality of the code have not been changed.

3.2 GENERIC REQUIREMENTS

For all of the modified ECPs, the PRIME-based properties will be added as an option, while the current formulation will be retained for backward compatibility and sensitivity studies. For each affected code, the PRIME property formulation will be tested via unit testing or code review to confirm that the correct properties have been implemented. The acceptance criteria for this examination is that the formulation reproduces the PRIME properties for the expected range of application. Additionally, a small number of simulations using the current properties and new PRIME property inputs will be run as both a regression test to the prior code version and a sensitivity confirmation. The sensitivity test is intended to be representative, such that a comprehensive requalification is deemed unnecessary.

Following or in parallel to this testing of the ECP, implementation testing within each functional area will be conducted. The purpose of this testing is to establish the following elements of impact:

- Process changes necessary to provide the additional inputs (e.g. exposure) to exercise the PRIME thermal property formulations.
- Comparison of the application process using PRIME properties versus existing properties.
- Comparison of the application process sensitivity compared to the application sensitivity based on TRACG[34] (see additional considerations in Section 3.3).
- Determination of the significance of the changes considering the process for including uncertainties in the application methodology (see additional considerations in Section 3.3).

These elements of impact will be subsequently examined by a process of independent verification or design review to recommend the final application process.

3.3 SPECIFIC REQUIREMENTS BY METHODOLOGY

3.3.1 Steady State Nuclear Methods

PRIME will be used to prepare new heat flux tables for comparison with existing GSTRM based heat flux tables. Examination of any additional dependencies (e.g. exposure) will be a part of this investigation.

If the PRIME relationships demonstrate a statistically significant bias relative to the GSTRM relationships, a representative plant fully loaded with GNF fuel will be chosen for exposure accounting comparison of hot and cold eigenvalues and TIPs. Changing the Doppler relationship may lead to different exposure accrual so a burn-in period of one or more cycles will be required before a consistent analysis can be made.

3.3.2 Transient Analysis

Representative analyses, with current and PRIME-based fuel properties, will be performed with ODYN and TASC in order to assess the impact and determine the need for further testing. In particular, the limiting reload licensing transients for a single plant with ODYNM10 and another plant with ODNYV09 will be performed. Note that the MCPR transients will test the PRIME-based fuel properties in TASC. Additionally, an ATWS simulation will be performed with an ODYNM10 plant and an ODYNV09 plant. The peak clad temperature evaluation portion of the ATWS simulations provides a test of TASC for this application.

3.3.3 Stability

Since ODYSY is a frequency domain code, comparisons and determination of the significance of the changes will be based on decay ratio evaluations. Representative analyses, with current and PRIME-based fuel properties, will be performed with ODYSY in order to assess the impact and determine the need for further testing. In particular, the limiting cases in representative reload licensing stability analyses for one Option I-D, one Option II, one Option-III and one DSS-CD plant (or application) will be performed with ODYSY05.

3.3.4 LOCA/ECCS Performance

The impact of using PRIME properties instead of GSTRM properties will be treated as a change in the approved methodology, per the reporting requirements of 10CFR50.46. The impact of this change can be conservatively estimated from the stored energy sensitivities that are carried out as a part of the Upper Bound PCT and oxide thickness calculations. These calculations in the SAFER/GESTR methodology adjust the nominal PCT to account for modeling and plant variable biases and uncertainties.

In some cases, if the conservative estimate results in a PCT that exceeds the regulatory limit, more detailed calculations will be performed to take into account effects such as exposure dependence, or plant-specific inputs. When PRIME is implemented in the SAFER ECP, this conservative estimate will no longer be necessary. The calculations will be based on the updated models.

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