ENCLOSURE 2

MFN 07-040

Part 21 Notification: Adequacy of GE Thermal-Mechanical Methodology, GSTRM

Non-Proprietary Version

IMPORTANT NOTICE

This is a non-proprietary version of Enclosure 1 to MFN 07-040, which has the proprietary information removed. Portions of the RAI responses that have been removed are indicated by an open and closed bracket as shown here [[ ]].

Evaluation of GE Thermal-Mechanical Methodology, GSTRM

Introduction

GE/GNF currently perform fuel rod thermal-mechanical design and licensing analyses with the GESTR-Mechanical (GSTRM) code and its associated application methodology. GSTRM[1] provides best estimate predictions of fuel rod thermal-mechanical performance. It is incorporated into design and licensing analyses with appropriate uncertainties and limits. GE/GNF is in the process of licensing a new model (PRIME[2]) to perform fuel rod thermal-mechanical modeling, but GSTRM is the current NRC-approved model.

During the ESBWR design certification review, NRC staff identified a potential non-conservatism in the GSTRM thermal-mechanical calculations supporting the GE14 fuel design. Specifically, the GSTRM code predictions for fuel temperature for the GE14 fuel rod are lower than those predicted by PRIME and the NRC staff's own confirmatory analysis. The NRC staff was concerned that GSTRM is under predicting fuel centerline temperature and that if GSTRM were to be qualified against higher exposure data, the weakness in GSTRM would become apparent. This impacts the NRC staff review of NEDC-33173P, "Applicability of GE Methods to Expanded Operating Domains," since that evaluation relies on GSTRM analyses.

The NRC staff requested that GE evaluate the overall conservatism in the GSTRM model for prediction of fuel temperature, using the same data that has been used to qualify PRIME. They requested that GE also demonstrate the impact of exposure on UO_2 thermal conductivity in fuel thermal-mechanical calculations, fuel design analyses, and downstream safety analyses.

Evaluation

Qualification of the GSTRM fuel rod thermal-mechanical performance was performed over a wide range of duty conditions, dimensional conditions and fabrication parameters to confirm the robustness of the embodied fundamental physical process and mechanism representations. The range of conditions included in the experimental qualification database extends well beyond commercial fuel rod application conditions. Table 1 provides a summary of the GSTRM qualification database. The experimental qualification included comparison of predictions to:

(1) Fuel temperatures as obtained by placement of, and continuous measurement by, a fuel thermocouple in the center of the fuel pellet column,
(2) Cladding diametral deformation as obtained by diametral profilometry performed at various times during normal steady-state operation as well as before and after intentional power ramps,

(3) Cladding axial deformation as obtained either by continuous on-line Linear Variable Differential Transducer (LVDT) length measurement or periodic conventional length measurements,

(4) Fission gas release as measured by fuel rod puncture, gas collection, and gas chromatography to determine the amount and composition of released gases, and

(5) Fuel rod internal pressure, as measured continuously by a bellows pressure transducer located in the fuel rod fission gas plenum.

Table 1: GSTRM Qualification Database

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The results of the GSTRM experimental qualification have been previously provided to the USNRC[3,4]. The fuel temperature qualification data is provided in Figures 1 and 2. These figures demonstrate excellent fuel temperature prediction capability that is unbiased both overall and as a function of exposure over the qualification range. [[

]]. Due to the reliability limitations of dissimilar metal in reactor fuel thermocouples, the fuel temperature qualification database was limited to [[ ]] at the thermocouple fuel node although the actual maximum exposure achieved within the measured fuel rods is somewhat higher. This extensive qualification of the temperature prediction capability confirmed the GSTRM model to be a reliable best-estimate predictor of fuel rod thermal-mechanical performance and [[
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Figure 1: GSTRM Fuel Temperature Qualification

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Figure 2: GSTRM Predicted/Measured Fuel Temperature versus Exposure

The PRIME fuel rod thermal-mechanical model has been developed specifically to address high exposure effects such as exposure-dependent fuel thermal conductivity and pellet rim formation. PRIME includes additional fuel performance model improvements such as an improved gadolinia fuel thermal conductivity relation as derived from laser flash thermal diffusivity measurements and qualified against in-reactor gadolinia fuel centerline temperature measurements. [[

]]. The PRIME fuel temperature qualification database includes additional fuel temperature measurements not available at the time of the GSTRM qualification. The large number of additional high and low exposure data increase the PRIME prediction uncertainty relative to GSTRM, however, it provide an overall unbiased fuel temperature prediction to a higher exposure.

In response to the NRC staff concern, GSTRM has been compared to the expanded exposure data that was used in the qualification of PRIME. The results of this evaluation for both GSTRM and PRIME are shown in Figure 3. [[

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Figure 3: GSTRM and PRIME Predicted/Measured Fuel Temperature versus Exposure for Extended Exposure Range

An additional comparison of PRIME and GSTRM was performed for two Halden experimental cases (IFA-432 Rod 1 and IFA-411-B1). [[

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Comparison of GSTRM and PRIME predictions with the online thermocouple measurements for the IFA-411-B1 and IFA-432 Rod 1 are shown in Figures 4 and 5. GSTRM predictions show no indication of a bias in predictive capability with exposure. [[

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Figure 4: GSTRM and PRIME Predicted Fuel Centerline Temperature for IFA-411-B1

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Figure 5: GSTRM and PRIME Predicted Fuel Centerline Temperature for IFA-432 Rod1

Licensing Parameters Impacted by GSTRM

GSTRM is intended to be a best estimate code, with uncertainty addressed explicitly in specific thermal-mechanical analyses where GSTRM is applied. The following parameters are primarily impacted by the GSTRM model:

Fuel centerline temperature
Cladding strain
Loss-of-coolant accident response
Fuel rod internal pressure

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]]. Therefore, this analysis concludes that the transient and stability analyses would be either not affected or conservative and GSTRM is adequate for such analyses. An evaluation of the impact of the GSTRM model is provided below for each of the primary parameters.

Fuel Centerline Temperature

The design and licensing limit on fuel temperature is that the maximum fuel centerline temperature cannot exceed the fuel melting temperature during normal operation, including anticipated operational occurrences (AOOs). Although it has been well demonstrated in numerous irradiation experiments that extended operation with significant fuel pellet central melting does not result in damage to the fuel rod cladding, this fuel temperature limit is applied to ensure that sudden shifting of molten fuel in the interior of the fuel rods, and subsequent potential cladding damage, is precluded.

The possible under prediction of fuel rod temperature has a negligible impact on fuel designs relative to compliance with design limits for the following reasons:

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Figure 6: GSTRM and PRIME Predicted/Measured Fuel Centerline Temperature vs. Exposure Compared to Peak LHGR

2. Thermal Overpower (TOP) and Mechanical Overpower (MOP) limits were developed to provide parameters that are easily evaluated in terms of LHGR and that can be used as computational limits during design of a core. [[

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3. All fuel rod thermal-mechanical analyses are evaluated to ensure that operation within that power-exposure envelope (i.e. local linear heat generation rate as a function of local exposure) will conform to the fuel rod thermal-mechanical design and licensing criteria. [[

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4. [[

]]. This provides additional assurance that GSTRM provides conservative results with adequate protection against fuel centerline melting.

Cladding Strain

The design and licensing limit on cladding strain is that the calculated cladding plastic strain at the pellet mid-height location cannot exceed 1% during normal operation, including AOOs. This limit is applied to ensure that fuel rod failure due to pellet-cladding mechanical interaction will not occur. [[

]]. Thus the GSTRM based MOP limit is conservative and adequate to ensure that cladding plastic strain is maintained less than the limit.

Loss-of-Coolant Accident (LOCA) Response

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]]. Thus, it is concluded that the impact on local oxidation in LOCA evaluations is also negligible.

Fuel Rod Internal Pressure

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]]. The fuel rod is filled with helium during manufacture to a specified fill gas pressure. During the initial rise to power, the fuel rod internal pressure increases due to the corresponding increase in the gas average temperature and the reduction in the fuel rod void volume resulting from fuel pellet expansion and inward cladding elastic deflection caused by the higher reactor coolant pressure. As exposure accumulates, the fuel rod internal pressure progressively increases due to the release of gaseous fission products from the fuel pellets into the fuel rod void volume. With higher exposure, a potential adverse thermal feedback condition may arise due to excessive fuel rod internal pressure. If the fuel rod internal pressure exceeds the coolant pressure, the resulting cladding tensile hoop stress causes the cladding to deform outward (cladding creepout). If the rate of this cladding outward deformation (cladding creepout rate) exceeds the rate at which the fuel pellet expands due to irradiation swelling (fuel swelling rate), the pellet-cladding gap will begin to open. An increase in the pellet-cladding gap would reduce the pellet-cladding thermal conductance, thereby increasing fuel temperatures. The increased fuel temperatures would result in further fuel pellet fission gas release, greater fuel rod internal pressure, and, correspondingly, a faster rate of cladding outward deformation and gap opening. A limit on fuel rod internal pressure is applied to prevent this adverse feedback condition.

In order to ensure that the fuel rod internal pressure design and licensing criterion is met during actual reactor operation, the fuel rod is designed in a conservative manner using a number of bounding assumptions. [[

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]]. Thus the GSTRM statistical methodology in conjunction with the LHGR limit envelope ensures adequate fuel rod protection from high fuel rod internal pressure to the upper end of the GSTRM exposure application.

Summary and Conclusions

The fuel temperature predictive capability of GSTRM, when extended to higher exposure data available for the PRIME code qualification indicates that

(1) [[ ]], and
(2) [ ]].

The primary parameters in fuel thermal-mechanical calculations, fuel design analyses and downstream safety analyses that are impacted by fuel temperature are fuel centerline melting, cladding strain, loss-of-coolant accident (LOCA) response, and fuel rod internal pressure.

]]. Therefore, GSTRM and its associated statistical methodology are adequate for fuel licensing and design calculations within its qualification domain, as summarized in Reference 1.

Additionally, GNF has developed a new fuel rod thermal-mechanical model to support high exposure fuel designs (Reference 2). This model will be submitted to the NRC for review and

approval, and will be incorporated into the GNF new fuel rod design and licensing process upon such approval.

References

1. Acceptance for Referencing of Licensing Topical Report NEDE-24011-P-A Amendment 7 to Revision 6, GE Standard Application for Reactor Fuel Letter, C.O. Thomas (NRC) to J. S. Charnley (GE), MFN-036-85, March 1, 1985.

2. The PRIME Model for Analysis of Fuel Rod Thermal – Mechanical Performance, Part 1 (Technical Bases), NEDC-22356P.

3. J.S. Charnley, letter to R. Lobel, "Fuel Property and Performance Model Revisions", MFN- 170-84, December 14, 1984.

4. J.S. Charnley, letter to G. C. Lainas, "Fuel Property and Performance Model Revisions", MFN-027-086, April 7, 1986.