

# FAST-1.0: Integral Assessment

Developed under NQA-1-2017

March 2020

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## Abstract

An integral assessment has been performed to quantify the predictive capabilities of FAST, a thermal-mechanical nuclear fuel performance code designed to analyze fuel behavior from beginning of life to burnup levels allowed by the U.S. Nuclear Regulatory Commission (NRC). FAST code calculations are shown to compare satisfactorily to a preselected set of experimental data with both steady-state and anticipated operating occurrence (AOO) conditions.

This document describes the assessment of FAST-1.0, which is the latest version of FAST, released February 2020.

## Foreword

The ability to accurately calculate the performance of light water reactor (LWR) fuel rods under high burnup conditions is a major objective of the reactor safety research program being conducted by the U.S. Nuclear Regulatory Commission (NRC). To achieve this objective, the NRC has sponsored an extensive program of analytical computer code development. One product of this program is NRC's FAST code, which provides the ability to accurately calculate the high burnup response of LWR fuel rods.

The NRC also continues to sponsor both in-pile and out-of-pile experiments to benchmark and assess the analytical code capabilities. Over 100 new assessment cases were recently added to the integral assessment database, bringing the database total to 137 assessment cases. The new assessment cases use data from recent integral irradiation experiments and post-irradiation examination (PIE) programs which provided valuable information on modern cladding materials and high burnup fuel behavior.

This report documents an integral assessment performed using the latest version of FAST, FAST-1.0, to demonstrate the code's ability to accurately calculate the performance of newer fuel designs and operating conditions.

## Executive Summary

This document is Volume 2 of a three volume series that describes the FAST code and its assessment. Volume 1 [Porter et al., 2020] describes the FAST code along with input instructions. Volume 2 (this document) describes the integral code assessment, done by comparing the code predictions for fuel temperatures, fission gas release (FGR), rod internal void volume, fuel swelling, cladding creep/growth, cladding corrosion, and hoop strain to data from integral irradiation experiments and post-irradiation examination (PIE) programs. Volume 3 [Geelhood et al., 2020] describes the Material Library used by FAST. The cases used for code assessment were selected based on the following criteria:

- Well-characterized design and operational data were provided.
- The reported results spanned ranges of interest for both design and operating parameters.

Thus, the fuel rod cases were selected to represent both boiling water reactor (BWR) and pressurized water reactor (PWR) fuel types, with pellet-to-cladding gap sizes within, above, and below the normal range for power reactor rods. The fill gas is pure helium in most cases, but cases are included for which helium-xenon fill gas mixtures were used to assess the gap conductance model. The linear heat generation rates at beginning of life (BOL) range up to 60 [kW/m] (18 [kW/ft]), and during end of life (EOL) power ramps, they range up to 47 [kW/m] (14 [kW/ft]). The rod-average fuel burnups range up to 99 [GWd/MTU], but only up to 76 [GWd/MTU] for power ramp cases. However, the code is only considered validated to rod-average burnup of 62 [GWd/MTU]. The EOL FGR ranges from less than 1% to greater than 50% of the produced quantity.

The primary code assessment database (used also for benchmarking the thermal and FGR models) consists of 137 well-characterized fuel rods. These include 45 test rods that experienced EOL power ramps (used for FGR and cladding hoop strain) and 92 “steady-state” cases including uranium dioxide (UO<sub>2</sub>), mixed oxide (MOX) fuel, and uranium-gadolinia (UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub>) Halden rods used for fuel temperatures, and UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> rods used for FGR.

Five rods from the primary set were used to assess FAST predictions of EOL void volume. The cases selected include full-length power reactor rods and shorter test reactor rods. A mix of test reactor and power reactor rods was also used to assess the fuel volume change due to densification and swelling.

The FAST model for cladding waterside oxidation was evaluated against BWR Zircaloy-2 and PWR Zircaloy-4, ZIRLO<sup>®</sup>, and M5<sup>™</sup> rod data.

The FAST predictions of cladding hoop strain were assessed against 27 BWR and PWR rods that were power ramped in various test reactors.

The following conclusions about FAST were made as a result of this assessment:

- **Thermal:** Comparisons were made for BOL UO<sub>2</sub> temperature measurements and UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> temperature measurements as a function of burnup. Overall, FAST gave reasonable predictions of fuel centerline temperature for fuel rods with UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> fuel (standard deviation of less than 5% ).

- **Fission Gas Release:** Comparisons were made for the  $\text{UO}_2$  and MOX FGR measurements for rods with widely varying power levels and burnups. Overall, FAST gave reasonable predictions (within 5% FGR absolute) of fission gas release for fuel rods with  $\text{UO}_2$  and MOX fuel.
- **Internal Void Volume:** Comparisons were made to data from two commercial reactor and three test reactor fuel rods. The code predicted the two commercial rods well but overpredicted the BR-3 test rod data by approximately 20% (relative) on average.
- **Cladding Corrosion:** Comparisons were made to data from two commercial BWR rods with Zircaloy-2 cladding, two commercial PWR rods with Zircaloy-4 cladding, two commercial PWR rods with ZIRLO<sup>®</sup> cladding, and one commercial PWR rod with M5<sup>™</sup> cladding. The oxide corrosion predictions were very good and tend to bracket the data.
- **Cladding Hoop Strain:** The original hoop strain assessment cases that were available up to a burnup of around 45 [GWd/MTU] demonstrated that, on average, FAST slightly overpredicts cladding hoop strain by 0.1% strain. FAST overpredicted all the short hold times cases. Despite this overprediction, FAST provides reasonable hoop strain predictions up to 62 [GWd/MTU].

## Acronyms and Abbreviations

|       |  |
|-------|--|
| ADU   | Ammonium diuranate                     |
| AOO   | Anticipated operating occurrence       |
| ATR   | Advanced Test Reactor                  |
| AUC   | Ammonium uranyl carbonate              |
| BNFL  | British Nuclear Fuels, Ltd.            |
| BOL   | Beginning of life                      |
| BWR   | Boiling water reactor                  |
| DNB   | Departure from nucleate boiling        |
| EOL   | End of life                            |
| FGR   | Fission gas release                    |
| GNF   | Global Nuclear Fuel                    |
| HBEP  | High Burnup Effects Program            |
| HBWR  | Heavy boiling water reactor            |
| HUHB  | Halden Ultra High Burnup               |
| LHGR  | Linear heat generation rate            |
| LOCA  | Loss-of-coolant accident               |
| LWR   | Light water reactor                    |
| MIMAS | Micronized master blend                |
| NRC   | U.S. Nuclear Regulatory Commission     |
| PCMI  | Pellet/Cladding Mechanical Interaction |
| PIE   | Post-irradiation examination           |
| PNNL  | Pacific Northwest National Laboratory  |
| PWR   | Pressurized water reactor              |
| SBR   | Short binderless route                 |
| SCIP  | Studsvik Cladding Integrity Program    |
| SPND  | Self-powered neutron detector          |
| TCD   | Thermal conductivity degradation       |
| TD    | Theoretical density                    |



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## 1.0 Introduction

This report is Volume 2 of a two volume series that describes the FAST code and its assessment. Volume 1 [Porter et al., 2020] describes the FAST code. This document describes the assessment of the integral performance of FAST.

This report provides the results of the assessment of the integral code predictions to measured data for fuel temperatures, fission gas release (FGR), internal void volume, cladding deformation, oxidation, and hydriding. The benchmark datasets are described in Section 2.0. Appendix A describes each set of benchmark data and gives the code input for each data comparison. The benchmark data are drawn from a wide range of burnup levels and operating conditions that are relevant to commercial operations. Experimental fuel rods with linear heat generation rates (LHGRs) at or near the maxima for commercial fuel operations were selected because the U.S. Nuclear Regulatory Commission (NRC) licenses fuel to the most limiting rod in the core. Not all the data selected are at limiting conditions. Some of the cases involve commercial fuel rods that operated at normal commercial operating conditions, which are significantly less than the limiting conditions. Also, it is noted that most of the thermal and FGR benchmark cases are drawn from experimental programs that involved numerous fuel rods, of which only a few were selected as benchmark cases. This was either because the rods in a given group were all irradiated under similar conditions and had similar FGR or because only rods with design parameters and operating conditions similar to current commercial practice were selected.

The integral code assessments include comparison to fuel temperature data in Chapter 3.0 and FGR data in Section 4.0. Comparisons of code predictions to internal void volume, cladding corrosion and hydriding, and hoop strain data are given in Chapters 5.0, 6.0, and 7.0 respectively. A summary and conclusions are found in Chapter 8.0.

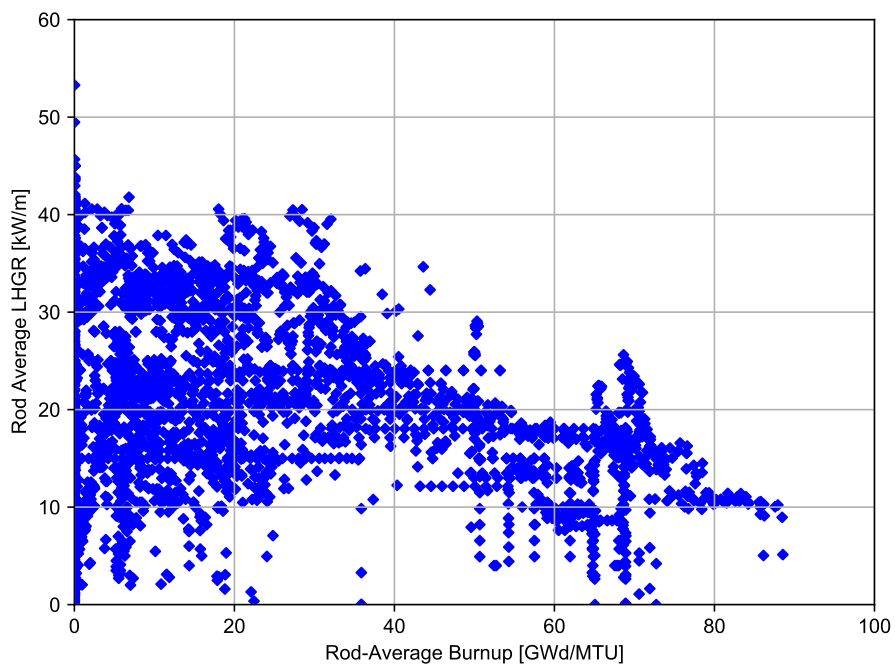
## 2.0 Assessment Data Description

A total of 137 benchmark cases (fuel rods) that have post-irradiation examination (PIE) were selected for the integral assessment of the FAST code. These include 92 fuel rods with steady-state power operation covering a wide range of burnup and 45 fuel rods with steady-state irradiations followed by an end of life (EOL) power ramp. The purpose of the code assessment was to assess the code against a limited set of well-qualified data that span the range of limiting operational conditions for commercial light water reactors (LWRs) to verify that the code adequately predicts the integral data. The integral data of interest were fuel temperatures, FGR, corrosion, void volumes, and cladding deformation. The cases in this relatively limited group were selected using criteria regarding the completeness and the quality of the rod performance data, as follows:

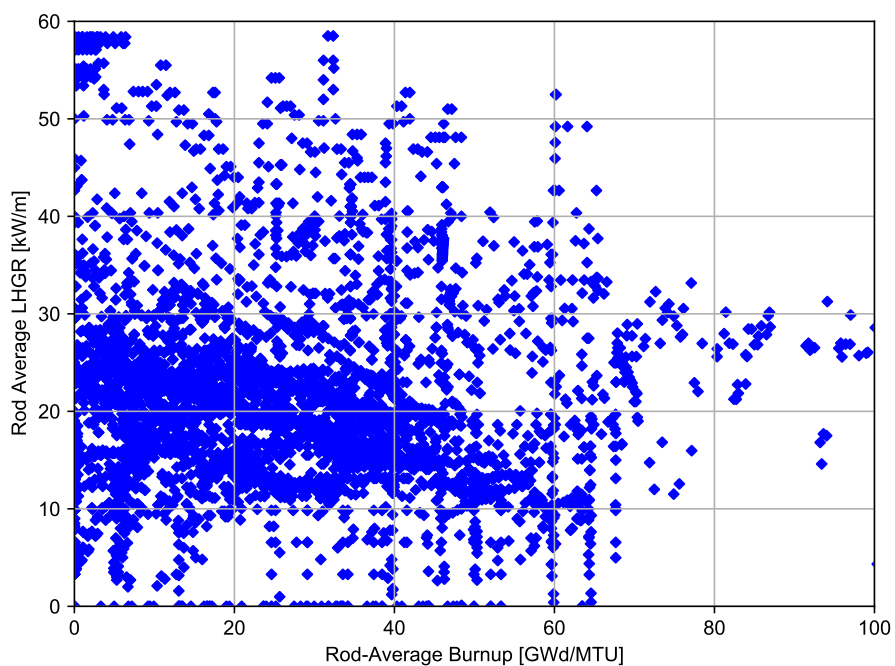
- The cases should all provide pre-irradiation characterization with well-qualified fuel rod powers, and some data should include PIE data of interest (e.g., FGR, cladding dimensional changes).
- Cases for temperature assessment should provide well-qualified fuel centerline temperature data as a function of time or burnup to verify fuel temperature predictions.
- Cases ranging from low to high fuel burnup, as well as low to high (limiting) LHGR, should be provided to cover the operating ranges for LWR operation for each fuel performance issue of interest (e.g., fuel temperature, FGR, deformation).
- Cases should provide cladding oxidation, hydriding, and deformation under prototypic pressurized water reactor (PWR) and boiling water reactor (BWR) conditions.
- Cases should demonstrate the effects (FGR and cladding deformation) of normal operational transients, and overpower transients including anticipated operational occurrences (AOOs) at low and high burnup.

The selected cases fulfill the above criteria, and they provide a mix of well-qualified test reactor data and less qualified (fuel rod power uncertainties are generally greater) commercial power reactor rod data.

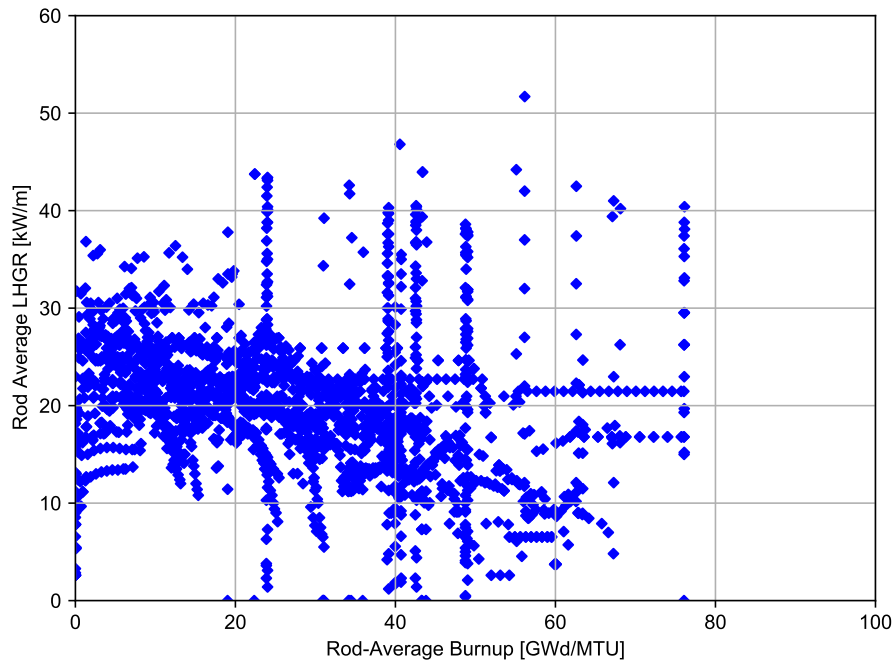
Figures 2-1, 2-2, and 2-3 show the rod-average LHGRs as a function of rod-average burnup (from full power histories of all the rods) for the rods in the temperature, FGR, and hoop strain assessment databases, respectively. These figures demonstrate the range of burnup and LHGRs to which the FAST predictions have been qualified for each of these integral code predictions. For the code prediction of cladding corrosion, the predictions are a function of time, power level, and coolant temperature. FAST has been qualified to predict cladding corrosion of Zircaloy-2 under BWR conditions beyond a rod-average burnup of 62 [GWd/MTU], and Zircaloy-4, ZIRLO<sup>®</sup>, and M5<sup>™</sup> under PWR conditions beyond a rod-average burnup of 70 [GWd/MTU] for 12 [ft] cores. The outlet temperature of 14 [ft] reactor cores may be higher than has been assessed for FAST, and the corrosion predictions at these temperatures have not been assessed.



**Figure 2-1.** Rod-average LHGR vs. rod-average burnup for temperature assessment cases



**Figure 2-2.** Rod-average LHGR vs. rod-average burnup for fission gas release assessment cases



**Figure 2-3.** Rod-average LHGR vs. rod-average burnup for hoop strain assessment cases

## 2.1 Description of the Steady-State Cases

The steady-state assessment cases are listed in Table 2-1 and the EOL burnup and fuel type are given for each case. This table presents the steady-state fuel behavior phenomena that are assessed in this report and indicates which cases are used for that assessment. An “X” in a table cell indicates that the corresponding data comparison was performed for a particular case to assess code predictions.

Detailed information and FAST input files for each case are found in Appendix A.1.

**Table 2-1. Steady-state fuel rod data cases used for FAST integral assessment**

| Reactor     | Reference                          | Rod           | Fuel Type                                       | Rod-Average Burnup [GWD/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|-------------|------------------------------------|---------------|---|------------------------------|--------------------|-------------|-----|-------------|-----------|
| Halden HBWR | [Lanning, 1986]                    | IFA-432r1     | UO <sub>2</sub>                                 | 45                           | X                  | X           | -   | -           | -         |
|             |                                    | IFA-432r2     | UO <sub>2</sub>                                 | 30                           | -                  | X           | -   | -           | -         |
|             |                                    | IFA-432r3     | UO <sub>2</sub>                                 | 45                           | X                  | X           | -   | -           | -         |
| Halden HBWR | [Bradley et al., 1981]             | IFA-513r1     | UO <sub>2</sub>                                 | 12                           | X                  | X           | -   | -           | -         |
|             |                                    | IFA-513r6     | UO <sub>2</sub>                                 | 12                           | X                  | X           | -   | -           | -         |
| Halden HBWR | [Rø and Rossiter, 2005]            | IFA-633r1     | UO <sub>2</sub>                                 | 40                           | -                  | X           | -   | -           | -         |
|             |                                    | IFA-633r3     | UO <sub>2</sub>                                 | 40                           | -                  | X           | -   | -           | -         |
|             |                                    | IFA-633r5     | UO <sub>2</sub>                                 | 40                           | -                  | X           | -   | -           | -         |
| Halden HBWR | [Thérache, 2005]<br>[Jošek, 2008a] | IFA-677.1r2   | UO <sub>2</sub>                                 | 32                           | X                  | X           | -   | -           | -         |
|             |                                    | IFA-677.1r3   | UO <sub>2</sub>                                 | 6                            | -                  | X           | -   | -           | -         |
|             |                                    | IFA-677.1r4   | UO <sub>2</sub>                                 | 6                            | -                  | X           | -   | -           | -         |
|             |                                    | IFA-677.1r6   | UO <sub>2</sub>                                 | 7                            | -                  | X           | -   | -           | -         |
| Halden HBWR | [Wiesenack, 1992]                  | IFA-562r18    | UO <sub>2</sub>                                 | 76                           | X                  | -           | -   | -           | -         |
| Halden HBWR | [Matsson and Turnbull, 1998]       | IFA-597r8     | UO <sub>2</sub>                                 | 71                           | X                  | -           | X   | -           | -         |
| Halden HBWR | [Tverberg and Amaya, 2001]         | IFA-515.10rA1 | UO <sub>2</sub>                                 | 80                           | X                  | -           | -   | -           | -         |
|             |                                    | IFA-515.10rA2 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 80                           | X                  | -           | -   | -           | -         |
|             |                                    | IFA-515.10rB1 | UO <sub>2</sub>                                 | 80                           | X                  | -           | -   | -           | -         |

**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor | Reference | Rod           | Fuel Type                                       | Rod-Average Burnup [GWd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|---------|-----------|---------------|---|------------------------------|--------------------|-------------|-----|-------------|-----------|
|         |           | IFA-515.10rB2 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 80                           | X                  | -           | -   | -           | -         |

**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor     | Reference  | Rod             | Fuel Type                                       | Rod-Average Burnup [Gwd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|-------------|--|-----------------|---|------------------------------|--------------------|-------------|-----|-------------|-----------|
| Halden HBWR | [Klecha, 2006]                                     | IFA-681r1       | UO <sub>2</sub>                                 | 33                           | X                  | X           | -   | -           | -         |
|             |  | IFA-681r2       | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 23                           | X                  | -           | -   | -           | -         |
|             |  | IFA-681r3       | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 12                           | X                  | -           | -   | -           | -         |
|             |  | IFA-681r4       | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 22                           | X                  | -           | -   | -           | -         |
|             |  | IFA-681r5       | UO <sub>2</sub>                                 | 32                           | X                  | -           | -   | -           | -         |
|             |  | IFA-681r6       | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 13                           | X                  | -           | -   | -           | -         |
| Halden HBWR | [Turnbull and White, 2002]                         | IFA-558r6       | UO <sub>2</sub>                                 | 41                           | X                  | -           | -   | -           | -         |
| Halden HBWR | [White, 1999]                                      | IFA-629-1r1     | MOX   | 33                           | X                  | -           | -   | -           | -         |
|             |  | IFA-629-1r2     | MOX   | 29 (FGR) 40 (Thermal)        | X                  | -           | X   | -           | -         |
| Halden HBWR | [Beguin, 1999] [Fujii and Claudel, 2001]           | IFA-610.2       | MOX   | 56                           | X                  | -           | -   | -           | -         |
|             |  | IFA-610.4       | MOX   | 57                           | X                  | -           | -   | -           | -         |
| Halden HBWR | [Claudel and Huet, 2001]                           | IFA-648.1r1     | MOX   | 62                           | X                  | -           | -   | -           | -         |
|             |  | IFA-648.1r2     | MOX   | 62                           | X                  | -           | -   | -           | -         |
| Halden HBWR | [Petiprez, 2002]                                   | IFA-629.3r5     | MOX   | 72                           | X                  | -           | X   | -           | -         |
|             |  | IFA-629.3r6     | MOX   | 68                           | X                  | -           | X   | -           | -         |
| Halden HBWR | [Mertens et al., 1998] [Mertens and Lippens, 2001] | IFA-606 Phase 2 | MOX   | 49                           | X                  | -           | X   | -           | -         |



**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor     | Reference  | Rod           | Fuel Type                                       | Rod-Average Burnup [GWd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|-------------|--|---------------|---|------------------------------|--------------------|-------------|-----|-------------|-----------|
| Halden HBWR | [Tverberg et al., 2005]                          | IFA-636r2     | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 25                           | X                  | -           | -   | -           | -         |
|             |  | IFA-636r4     | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 25                           | X                  | -           | -   | -           | -         |
| BR-3 PWR    | [Balfour, 1982] [Balfour et al., 1982]           | 24i6          | UO <sub>2</sub>                                 | 60.1                         | -                  | -           | X   | X           | -         |
|             |  | 36i8          | UO <sub>2</sub>                                 | 61.5                         | -                  | -           | X   | X           | -         |
|             |  | 111i5         | UO <sub>2</sub>                                 | 48.6                         | -                  | -           | X   | X           | -         |
|             |  | 28i6          | UO <sub>2</sub>                                 | 53.3                         | -                  | -           | X   | -           | -         |
|             |  | 30i8          | UO <sub>2</sub>                                 | 57.85                        | -                  | -           | X   | -           | -         |
| DR-3 PWR    | [Bagger et al., 1978]                            | m2-2c         | UO <sub>2</sub>                                 | 43.75                        | -                  | -           | X   | -           | -         |
|             |  | pa29-4        | UO <sub>2</sub>                                 | 47.39                        | -                  | -           | X   | -           | -         |
| BR-3 PWR    | [Lanning et al., 1987]                           | HBEF BNFL5-DH | UO <sub>2</sub>                                 | 42                           | -                  | -           | X   | -           | -         |
| BR-3 PWR    | [Barner et al., 1990]                            | HBEF BNFL-DE  | UO <sub>2</sub>                                 | 33.9                         | -                  | -           | X   | -           | -         |
| NRX PWR     | [de Meulemeester et al., 1973]                   | EPL-4         | UO <sub>2</sub>                                 | 10.4                         | -                  | -           | X   | -           | -         |
| NRX PWR     | [Notley et al., 1967] [Notley and MacEwan, 1965] | CBR           | UO <sub>2</sub>                                 | 2.7                          | -                  | -           | X   | -           | -         |
|             |  | CBY           | UO <sub>2</sub>                                 | 2.65                         | -                  | -           | X   | -           | -         |
|             |  | LFF           | UO <sub>2</sub>                                 | 3.29                         | -                  | -           | X   | -           | -         |
|             |  | CBP           | UO <sub>2</sub>                                 | 2.61                         | -                  | -           | X   | -           | -         |

**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor     | Reference   | Rod          | Fuel Type       | Rod-Average Burnup [Gwd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|-------------|---|--------------|-----------------|------------------------------|--------------------|-------------|-----|-------------|-----------|
| EL-3 PWR    | [Janvier et al., 1967]  | 4110-ae2     | UO <sub>2</sub> | 6.2                          | -                  | -           | X   | -           | -         |
| Zorita PWR  | [Balfour et al., 1982]  | 4110-be2     | UO <sub>2</sub> | 6.6                          | -                  | -           | X   | -           | -         |
| Halden HBWR | [Chantoin et al., 1997]   | 332          | UO <sub>2</sub> | 56.8                         | -                  | -           | X   | -           | -         |
| Halden HBWR | [Turnbull, 2001]  | FUMEX 6f     | UO <sub>2</sub> | 55.45                        | -                  | -           | X   | -           | -         |
| ANO-2 PWR   | [Smith et al., 1994]  | FUMEX 6s     | UO <sub>2</sub> | 55.45                        | -                  | -           | X   | -           | -         |
| Oconee PWR  | [Newman, 1986]  | IFA429DH     | UO <sub>2</sub> | 98.9                         | -                  | -           | X   | -           | -         |
| Halden HBWR | [Blair and Wright, 2004]  | TSQ002       | UO <sub>2</sub> | 53.2                         | -                  | -           | X   | X           | X         |
| ATR         | [Morris et al., 2000]<br>[Morris et al., 2001]<br>[Morris et al., 2005]<br>[Hodge et al., 2002]<br>[Hodge et al., 2003] | 15309        | UO <sub>2</sub> | 50                           | -                  | -           | X   | X           | X         |
|             |   | IFA-651.1r1  | MOX             | 22.41                        | X                  | -           | X   | -           | -         |
|             |   | IFA-651.1r3  | MOX             | 21.73                        | X                  | -           | X   | -           | -         |
|             |   | IFA-651.1r6  | MOX             | 20.27                        | X                  | -           | X   | -           | -         |
|             |   | PII C2 P5    | MOX             | 21                           | -                  | -           | X   | -           | -         |
|             |   | PIII C3 P6   | MOX             | 30                           | -                  | -           | X   | -           | -         |
|             |   | PIII C10 P13 | MOX             | 30                           | -                  | -           | X   | -           | -         |
|             |   | PIV C4 P7    | MOX             | 40                           | -                  | -           | X   | -           | -         |
|             |   | PIV C5 P8    | MOX             | 50                           | -                  | -           | X   | -           | -         |
|             |   | PIV C6 P9    | MOX             | 50                           | -                  | -           | X   | -           | -         |
|             |   | PIV C12 P15  | MOX             | 50                           | -                  | -           | X   | -           | -         |

**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor          | Reference   | Rod                   | Fuel Type | Rod-Average Burnup [GWd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|------------------|---|-----------------------|-----------|------------------------------|--------------------|-------------|-----|-------------|-----------|
| Gravelines-4 PWR | [Beguin, 1999] [Fuji and Claudel, 2001] [Claudel and Huet, 2001] [Petiprez, 2002] | N06                   | MOX       | 48                           | -                  | -           | X   | -           | -         |
|                  |   | N12                   | MOX       | 57                           | -                  | -           | X   | -           | -         |
|                  |   | P16                   | MOX       | 53                           | -                  | -           | X   | -           | -         |
| Halden HBWR      | [Wright, 2004]  | IFA 633.1r6           | MOX       | 32                           | X                  | -           | X   | -           | -         |
| Beznau-1         | [Cook et al., 2003] [Cook et al., 2004]   | M504 H8               | MOX       | 37.5                         | -                  | -           | X   | -           | -         |
|                  |   | M504 I2               | MOX       | 43                           | -                  | -           | X   | -           | -         |
|                  |   | M504 K9               | MOX       | 42.5                         | -                  | -           | X   | -           | -         |
|                  |   | M504 M9               | MOX       | 44.2                         | -                  | -           | X   | -           | -         |
| Beznau-1         | [Boulanger et al., 2004]  | M308 Segment 2        | MOX       | 57.5                         | -                  | -           | X   | -           | -         |
| Halden HBWR      | [Koike, 2004]   | IFA-597.4/.5/.6/.7r10 | MOX       | 35.7                         | X                  | -           | X   | -           | -         |
|                  |   | IFA-597.4/.5/.6/.7r11 | MOX       | 36.8                         | X                  | -           | X   | -           | -         |
| Fugen HBWR       | [Ozawa, 2004]   | E09 Rods Inner        | MOX       | 29.6                         | -                  | -           | X   | -           | -         |
|                  |   | E09 Rods Intermediate | MOX       | 39.3                         | -                  | -           | X   | -           | -         |
|                  |   | E09 Rods Outer        | MOX       | 42                           | -                  | -           | X   | -           | -         |

**Table 2-1.** Steady-state fuel rod data cases used for FAST integral assessment (continued)

| Reactor        | Reference  | Rod          | Fuel Type                                       | Rod-Average Burnup [GWd/MTU] | Thermal vs. Burnup | BOL Thermal | FGR | Void Volume | Corrosion |
|----------------|--|--------------|---|------------------------------|--------------------|-------------|-----|-------------|-----------|
| Monticello BWR | [Baumgartner, 1984]  | MTB99 Rod A1 | UO <sub>2</sub>                                 | 45                           | -                  | -           | -   | -           | X         |
| TVO-1 BWR      | [Barner et al., 1990]  | HBEP H8/36-6 | UO <sub>2</sub>                                 | 51.4                         | -                  | -           | -   | -           | X         |
| Vandellos PWR  | [CSN and ENUSA, 2002]  | A06          | UO <sub>2</sub>                                 | 68                           | -                  | -           | -   | -           | X         |
|                |  | A12          | UO <sub>2</sub>                                 | 68                           | -                  | -           | -   | -           | X         |
| Vandellos PWR  | [Segura and Bernaudat, 2002]   | N05          | UO <sub>2</sub>                                 | 70                           | -                  | -           | -   | -           | X         |
| BR-3/BR-2      | [Hoffmann and Kraus, 1984] [Manley et al., 1989] [Reindl et al., 1991] | GAIN Rod 301 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 38.8                         | -                  | -           | X   | -           | -         |
|                |  | GAIN Rod 302 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 37.79                        | -                  | -           | X   | -           | -         |
|                |  | GAIN Rod 701 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 38.9                         | -                  | -           | X   | -           | -         |
|                |  | GAIN Rod 702 | UO <sub>2</sub> -Gd <sub>2</sub> O <sub>3</sub> | 38.9                         | -                  | -           | X   | -           | -         |
| Ringhals 3     | [Schrire, 2018]  | R3-2AH3-D12  | UO <sub>2</sub>                                 | 33.3                         | -                  | -           | -   | X           | -         |
|                |  | R3-0AH5-E14  | UO <sub>2</sub>                                 | 57.82                        | -                  | -           | -   | X           | -         |
|                |  | R3-2AH3-D15  | UO <sub>2</sub>                                 | 34.1                         | -                  | -           | -   | X           | -         |
| Ringhals 2     | [Schrire, 2018]  | R2-AL06-D6   | UO <sub>2</sub>                                 | 27.97                        | -                  | -           | -   | X           | -         |
|                |  | R2-AD23-D5   | UO <sub>2</sub>                                 | 62.95                        | -                  | -           | -   | X           | -         |
|                |  | 07R2D5       | UO <sub>2</sub>                                 | 62.0                         | -                  | -           | -   | X           | -         |

## 2.2 Description of the Power-Ramp Cases

The power-ramp assessment cases are listed in Table 2-2, and the EOL burnup, fuel type, ramp terminal power level, and hold time are given for each case. This table presents the power-ramp fuel behavior phenomena that are assessed in this report and indicates which cases are used for that assessment. An “X” in a table cell indicates that the corresponding data comparison was performed for a particular case to assess code predictions.

Detailed information and FAST input files for each case is found in Appendix A.2.

**Table 2-2.** Power-ramped fuel rod data cases used for FAST integral assessment

| Base Irradiation/Ramp Testing | Reference  | Rod               | Fuel Type       | Rod-Average Burnup [GWd/MTU] | Ramp Terminal Level [kW/m] | Ramp Hold Time | FGR | Hoop Strain |
|-------------------------------|--|-------------------|-----------------|------------------------------|----------------------------|----------------|-----|-------------|
| Obringheim/Petten             | [Barner et al., 1990]                              | HBEP D200         | UO <sub>2</sub> | 25                           | 45.3                       | 2.4 days       | X   | -           |
|                               |  | HBEP D226         | UO <sub>2</sub> | 44                           | 45.0                       | 2.6 days       | X   | -           |
| Obringheim/Petten             | [Djurle, 1985]                                     | PK1/1             | UO <sub>2</sub> | 35.4                         | 37.2                       | 12 hr          | -   | X           |
|                               |  | PK1/3             | UO <sub>2</sub> | 35.2                         | 42.6                       | 12 hr          | -   | X           |
|                               |  | PK2/1             | UO <sub>2</sub> | 45.2                         | 36.8                       | 12 hr          | -   | X           |
|                               |  | PK2/3             | UO <sub>2</sub> | 44.6                         | 44.0                       | 12 hr          | -   | X           |
|                               |  | PK2-S             | UO <sub>2</sub> | 43.4                         | 44.0                       | 12 hr          | -   | X           |
|                               |  | PK4/1             | UO <sub>2</sub> | 33.7                         | 34.3                       | 12 hr          | -   | X           |
|                               |  | PK4/2             | UO <sub>2</sub> | 33.8                         | 39.2                       | 12 hr          | -   | X           |
|                               |  | PK6/1             | UO <sub>2</sub> | 36.7                         | 43.7                       | 1 hr           | -   | X           |
|                               |  | PK6/2             | UO <sub>2</sub> | 36.8                         | 35.7                       | 12 hr          | X   | X           |
|                               |  | PK6/3             | UO <sub>2</sub> | 36.5                         | 43.3                       | 12 hr          | X   | -           |
|                               |  | PK6/S             | UO <sub>2</sub> | 35.9                         | 41.0                       | 12 hr          | X   | -           |
| Studsvik/Studsvik             | [Mogard et al., 1979]<br>[Lysell and Birath, 1979] | Inter-Ramp Rod 16 | UO <sub>2</sub> | 21                           | 43.8                       | 24 hr          | X   | X           |
|                               |  | Inter-Ramp Rod 18 | UO <sub>2</sub> | 18                           | 37.79                      | 24 hr          | X   | X           |
| Halden/DR-2                   | [Knudsen et al., 1983]                             | RISØF14-6         | UO <sub>2</sub> | 27                           | 28.7                       | 3 days         | X   | -           |
|                               |  | RISØF7-3          | UO <sub>2</sub> | 35                           | 30.2                       | 17 hr          | X   | -           |
|                               |  | RISØF9-3          | UO <sub>2</sub> | 33                           | 29.7                       | 30 hr          | X   | -           |

**Table 2-2. Power-ramped fuel rod data cases used for FAST integral assessment (continued)**

| Base Irradiation/Ramp Testing | Reference   | Rod        | Fuel Type       | Rod-Average Burnup [GWd/MTU] | Ramp Terminal Level [kW/m] | Ramp Hold Time | FGR | Hoop Strain |
|-------------------------------|---|------------|-----------------|------------------------------|----------------------------|----------------|-----|-------------|
| Quad Cities 1 / DR3           | [Chantoin et al., 1997]   | ge2        | UO <sub>2</sub> | 41.9                         | 41.9                       | 38 hr          | X   | X           |
|                               |   | ge4        | UO <sub>2</sub> | 24.0                         | 24.0                       | 34 hr          | X   | X           |
|                               |   | ge6        | UO <sub>2</sub> | 42.3                         | 38.1                       | 5 days         | X   | X           |
|                               |   | ge7        | UO <sub>2</sub> | 41                           | 35.5                       | 4 hr           | X   | X           |
| ANO-1/Studsvik                | [Wesley et al., 1994]   | BW stud R1 | UO <sub>2</sub> | 62.3                         | 22.1                       | 12 hr          | X   | X           |
|                               |   | BW stud R3 | UO <sub>2</sub> | 62.1                         | 24.7                       | 12 hr          | X   | X           |
| Biblis A /DR3                 | [Chantoin et al., 1997]   | RISØAN1    | UO <sub>2</sub> | 41.3                         | 40.3                       | 3 days         | X   | X           |
|                               |   | RISØAN8    | UO <sub>2</sub> | 40.3                         | 30.1                       | 12 hr          | X   | X           |
| Gravelines-5/Siloe            | [Struzik, 2004]   | regate     | UO <sub>2</sub> | 50.2                         | 38.5                       | 1.5 hr         | X   | -           |
| Beznau-1/Petten               | [White et al., 2001]<br>[Cook et al., 2000]<br>[Cook et al., 2003]<br>[Cook et al., 2004] | M501 HR-1  | MOX             | 37                           | 38.1                       | 12 hr          | X   | X           |
|                               |   | M501 HR-2  | MOX             | 37                           | 35.7                       | 12 hr          | X   | -           |
|                               |   | M501 HR-3  | MOX             | 37                           | 46.2                       | 12 hr          | X   | -           |
|                               |   | M501 HR-4  | MOX             | 36                           | 47.0                       | 12 hr          | X   | -           |
|                               |   | M501 MR-1  | MOX             | 34                           | 38.1                       | 12 hr          | X   | -           |
|                               |   | M501 MR-2  | MOX             | 34                           | 41.9                       | 12 hr          | X   | -           |
|                               |   | M501 MR-3  | MOX             | 34                           | 40.5                       | 12 hr          | X   | -           |
|                               |   | M501 MR-4  | MOX             | 33                           | 41.7                       | 20 min         | X   | -           |

**Table 2-2. Power-ramped fuel rod data cases used for FAST integral assessment (continued)**

| Base Irradiation/Ramp Testing | Reference         | Rod   | Fuel Type       | Rod-Average Burnup [GWd/MTU] | Ramp Terminal Level [kW/m] | Ramp Hold Time | FGR | Hoop Strain |
|-------------------------------|-------------------|-------|-----------------|------------------------------|----------------------------|----------------|-----|-------------|
| Leibstadt/Studsvik            | [Kallstrom, 2005] | KKL-1 | UO <sub>2</sub> | 63                           | 42.5                       | 40 min         | X   | -           |
|                               |                   | KKL-2 | UO <sub>2</sub> | 67                           | 41                         | 30 s           | -   | X           |
|                               |                   | KKL-3 | UO <sub>2</sub> | 56                           | 52                         | 12 hr          | -   | X           |
| Ringhals/Studsvik             |                   | KKL-4 | UO <sub>2</sub> | 40                           | 45                         | 5 s            | -   | X           |
|                               |                   | M5-H1 | UO <sub>2</sub> | 67                           | 40                         | 5 s            | -   | X           |
| Oskarhamn/Studsvik            |                   | M5-H2 | UO <sub>2</sub> | 68                           | 40                         | 12 hr          | -   | X           |
| Vandellos/Studsvik            |                   | O2    | UO <sub>2</sub> | 55                           | 40                         | 30 s           | -   | X           |
|                               |                   | Z-2   | UO <sub>2</sub> | 76                           | 40                         | 6 hr           | -   | X           |
|                               |                   | Z-3   | UO <sub>2</sub> | 76                           | 40                         | < 1s*          | -   | X           |
|                               |                   | Z-4   | UO <sub>2</sub> | 76                           | 38                         | 6 hr           | -   | X           |



## 3.0 Thermal Behavior Assessment

Thermal predictions are important for calculating initial fuel stored energy, which is used as input to loss-of-coolant accident (LOCA) analyses. The fuel temperatures are also used to calculate FGRs and EOL rod pressures and to verify no fuel has melted. In general, PWR LOCA and fuel melt analyses are calculated with FAST to be more limiting at burnups between 25 and 35 [GWd/MTU], while the same analyses for BWRs are generally more limiting at burnups between 15 and 25 [GWd/MTU].

Comparisons of predicted and measured fuel centerline temperatures from instrumented Halden reactor test assemblies have been used to evaluate the code's ability to predict BOL temperatures and through-life temperature histories (i.e., rod power vs. burnup). The BOL and through-life temperature comparisons are separated because they have different biases and uncertainties (based on standard deviation) in the code thermal predictions. The through-life temperature history comparisons will be used to bound the uncertainties on PWR and BWR LOCA initialization and fuel melting analyses. The BOL temperature database includes not only rods with helium-filled gaps, but also rods with xenon- and xenon-helium-filled gaps and rods with pellet/cladding gap sizes both larger and smaller than typically used in commercial fuel designs. These variations in gap size and fill gas indicate that the code can properly account for the thermal resistance across the fuel cladding gap as a function of gap size and gas composition and is not just tuned to provide good results for typical LWR commercial fuel designs.

The comparisons of measured and predicted through-life fuel center temperature histories were done with two goals in mind. The first was to determine if the code properly accounts for the fuel thermal conductivity degradation (TCD) with burnup. The second goal was to determine if the code properly predicts the effect of thermal feedback on fuel temperature caused by gas release and consequent contamination of the initial helium fill gas with lower conductivity fission gas.

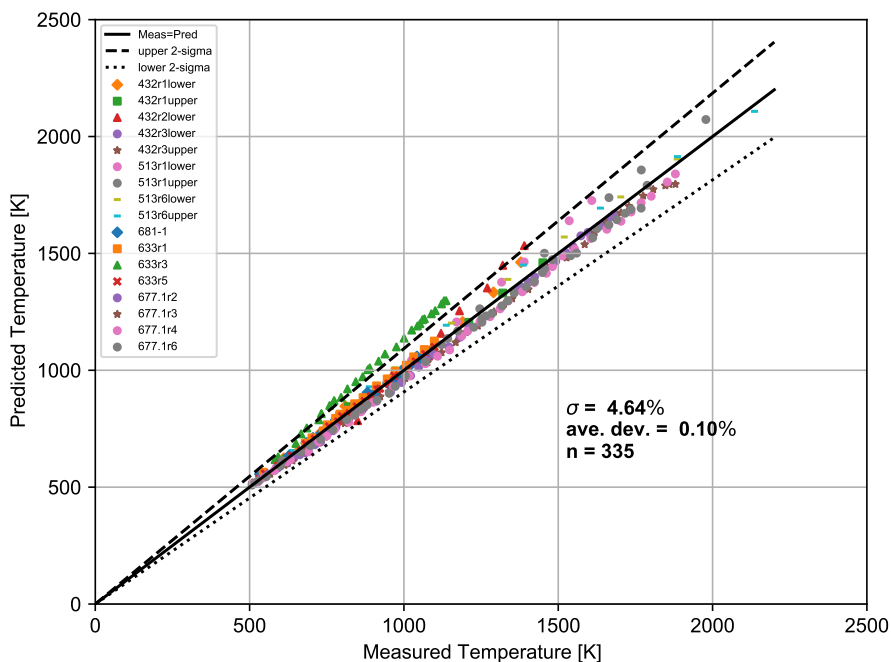
The BOL and through-life code-to-data comparisons are discussed separately in the following sections.

### 3.1 Temperature Predictions

The BOL fuel centerline temperature predictions are assessed against centerline temperature measurements taken during the first ramp to power. This power ramp occurs during the first 1 to 2 days of operation. Because of this, the initial fuel rod dimensions apply and there is no time for phenomena such as FGR, fuel densification and swelling, cladding creep, or cladding corrosion.

#### 3.1.1 UO<sub>2</sub> Temperature Predictions

FAST was assessed against BOL temperature measurements taken during the first ramp to power. Thirteen rods are used to assess the performance of FAST at BOL: IFA-432 rod 1, IFA-432 rod 2, IFA-432 rod 3, IFA-513 rod 1, IFA-513 rod 6, IFA-681 rod 1, IFA-633 rod 1, IFA-633 rod 3, IFA-633 rod 5, IFA-677.1 rod 2, IFA-677.1 rod 3, IFA-677.1 rod 4, and IFA-677.1 rod 6. Figure 3-1 shows the predicted vs. measured temperature for the BOL ramp up to power for the 13 assessment cases.



**Figure 3-1.** Measured and predicted centerline temperature for the first ramp to power for 13 assessment cases

This figure shows that FAST predicts these centerline temperatures within a standard error of 4.6% of the measured centerline temperature and no bias (and an average deviation  $\frac{\sum(P-M)/M}{n}$  of +0.03%). A standard error of 4.6% is reasonable given the uncertainty in the thermocouple data and the calculated rod power. The BOL fuel temperature assessment is an improvement over the FAST predictions due to the incorporation of a new fuel relocation model in FAST.

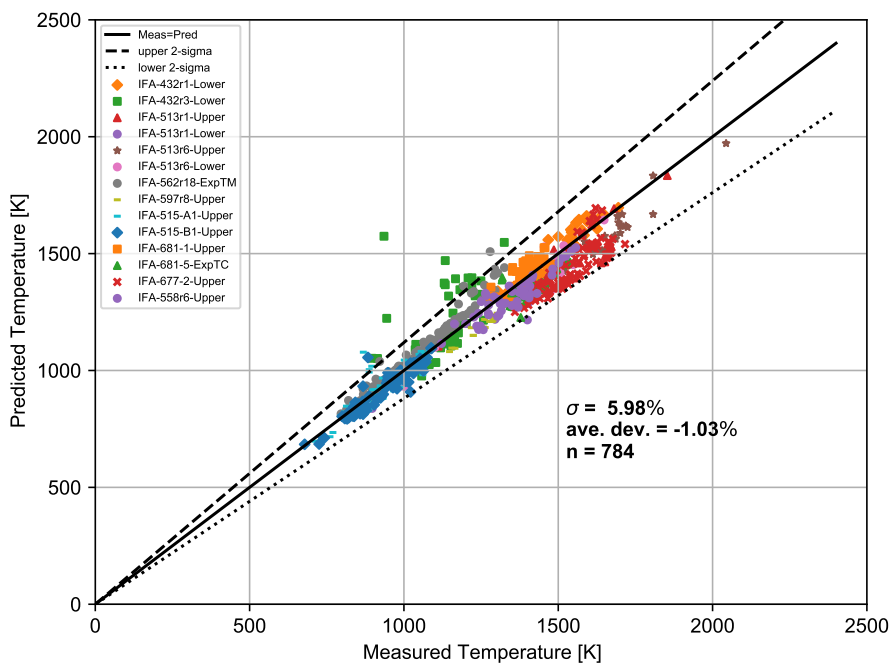
## 3.2 Assessment of Temperature Predictions as a Function of Burnup

### 3.2.1 UO<sub>2</sub> Centerline Temperature Predictions as a Function of Burnup

The assessment of FAST UO<sub>2</sub> temperature predictions was performed using the same cases that were used for the BOL assessment, with the following differences.

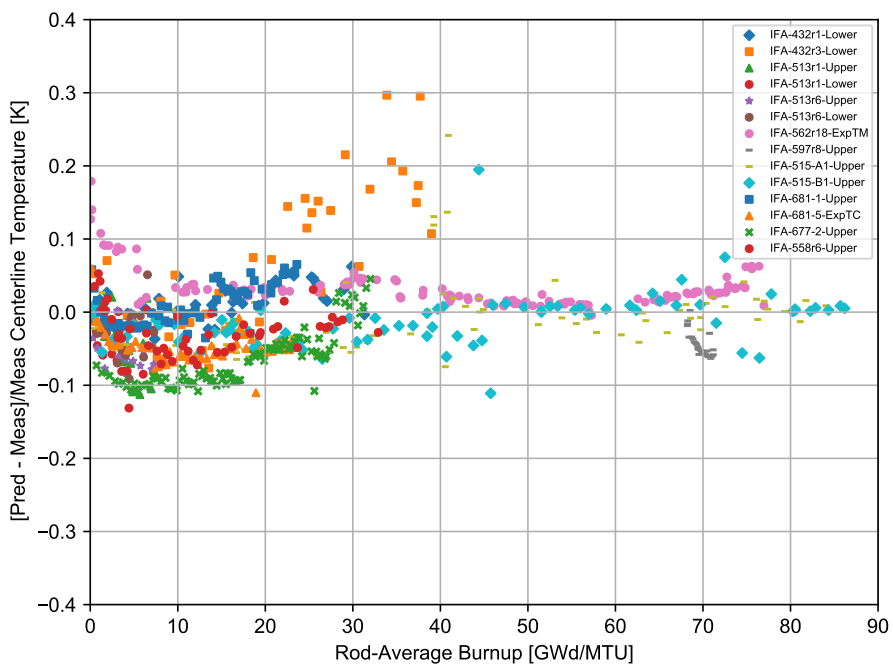
1. IFA-432 rod 2 has been removed as an assessment of FAST as a function of burnup, as the test is not prototypic of current fuel designs due to its large gap, and a small overprediction in FGR can result in a large temperature overprediction.
2. IFA-633 rods 1, 3, and 5 and IFA-677.1 rods 3, 4, and 6 originally only had BOL temperature reported and only recently had measured temperature as a function of burnup reported. Therefore, these rods are not included in this assessment.
3. IFA-562 rod 18, IFA-597 rod 8, IFA-515.10 rods A1 and B1, IFA-681 rod 5, and IFA-558 rod 6 have been added in addition to the BOL assessment cases.

The following figures show measured and predicted fuel centerline temperatures from rods with centerline temperature measurements. Individual rod predictions may demonstrate a systematic error (bias) that may be due to thermocouple decalibration or a systematic error in the power history or axial power shape (power at thermocouple location) provided due to decalibration in or with the neutron detectors. However, when all the comparisons are examined, it is found that there is no overall systematic error (bias) in the prediction of UO<sub>2</sub> fuel temperature throughout life, as can be seen in Figure 3-2. For all the cases, a standard error of 6.0% on the centerline temperature was calculated.



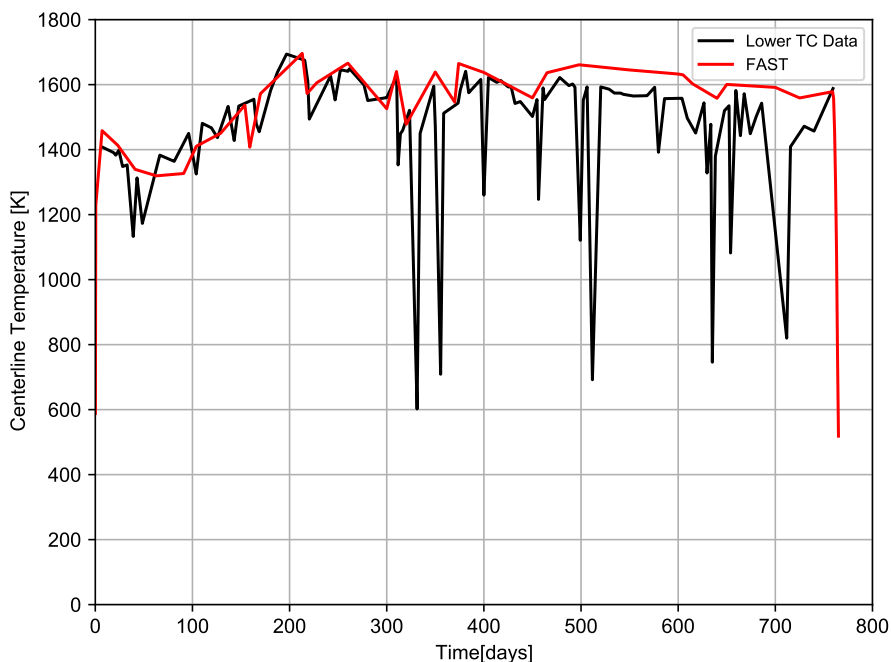
**Figure 3-2.** Measured and predicted centerline temperature for the UO<sub>2</sub> assessment cases throughout life

These data are also shown in terms of relative bias in Figure 3-3 as a function of burnup. There appears to be an underpredictive bias of 4.0% on average early in life between 2 and 16 [GWd/MTU]. However, there appears to be no systematic bias in the predictions with increasing burnup.



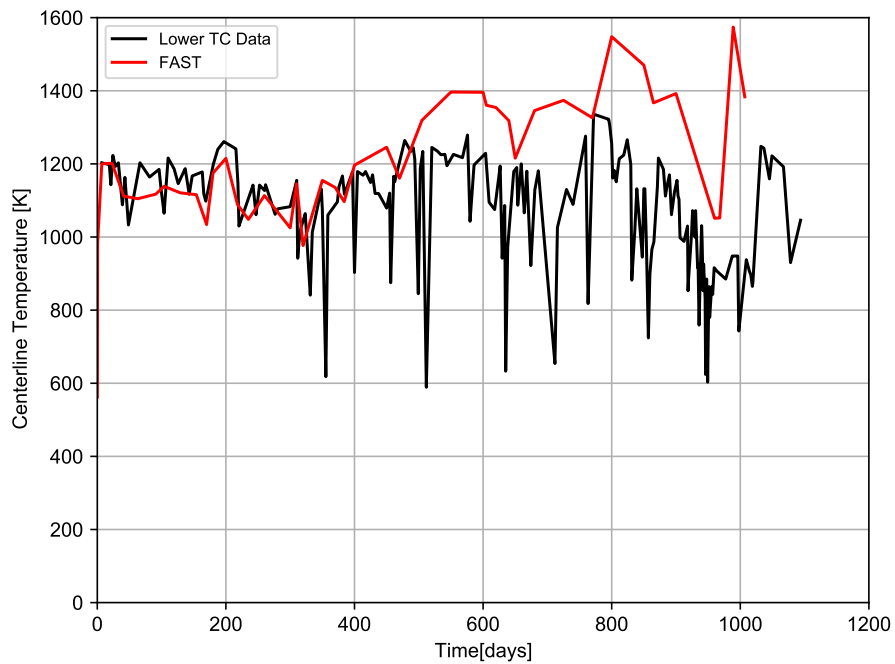
**Figure 3-3.** Predicted minus measured divided by measured centerline temperature for the UO<sub>2</sub> assessment cases as a function of burnup

Figure 3-4 shows the measured and predicted centerline temperature for IFA-432r1. This figure contains data from the lower thermocouple. This rod also contained an upper thermocouple, but it failed after 150 days. The comparisons to the upper thermocouple data are similar to the lower thermocouple. This figure shows excellent agreement between the FAST predictions and the data.



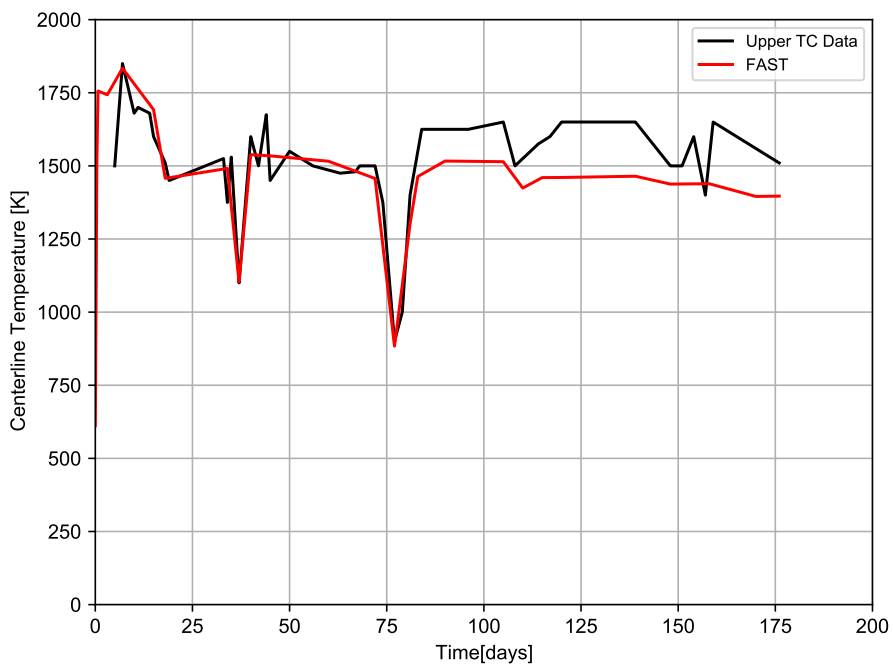
**Figure 3-4.** Measured and predicted centerline temperature for IFA-432 rod 1 UO<sub>2</sub> lower thermocouple (burnup = 45 [GWd/MTU], as-fabricated radial gap = 114 [ $\mu$ m])

Figure 3-5 shows the measured and predicted centerline temperature for IFA-432r3. This figure contains data from the lower thermocouple. This rod also contained an upper thermocouple, but it failed after 550 days. The comparisons to the upper thermocouple data are similar to the lower thermocouple. This figure shows excellent agreement between the FAST predictions and the data at BOL, and an overprediction of about 100 [K] (7% relative) at EOL. This overprediction may be due to FAST overpredicting the gas release, leading to higher predicted temperatures. As noted earlier, overprediction of gas release leads to lower gap conductivity and results in higher fuel temperature predictions. It should also be noted that some of the helium fill and fission gases were found to have leaked out of these IFA-432 rods based on rod puncture data (i.e., the leak was theorized to have occurred around the thermocouple penetrations through the end caps).

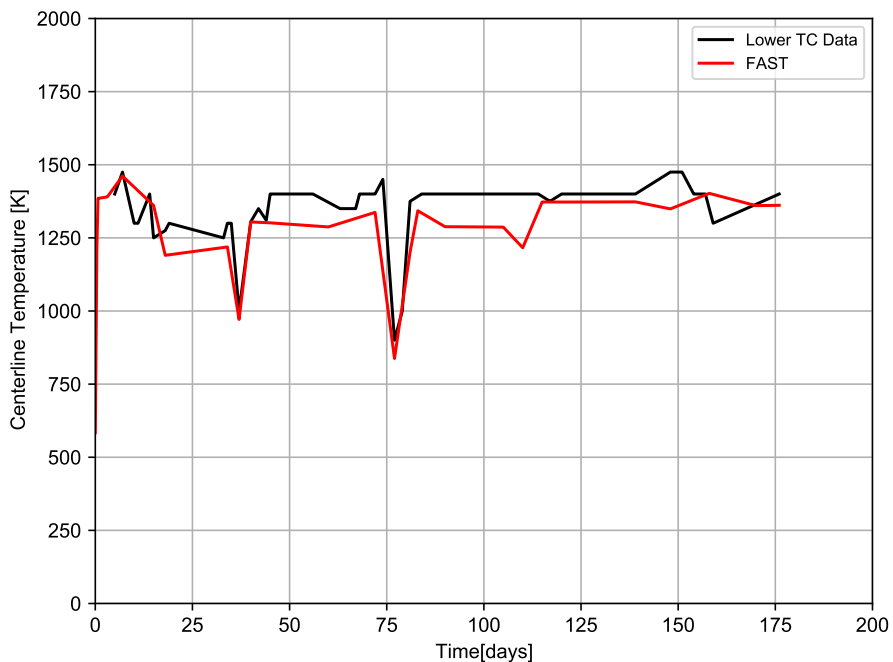


**Figure 3-5.** Measured and predicted centerline temperature for IFA-432 rod 3 UO<sub>2</sub> lower thermocouple (burnup = 45 [GWd/MTU], as-fabricated radial gap = 38 [ $\mu$ m])

Figures 3-6 and 3-7 show the measured and predicted centerline temperature for IFA-513r1. These figures contain data from the upper and lower thermocouples and show reasonable agreement between the FAST predictions and the data.



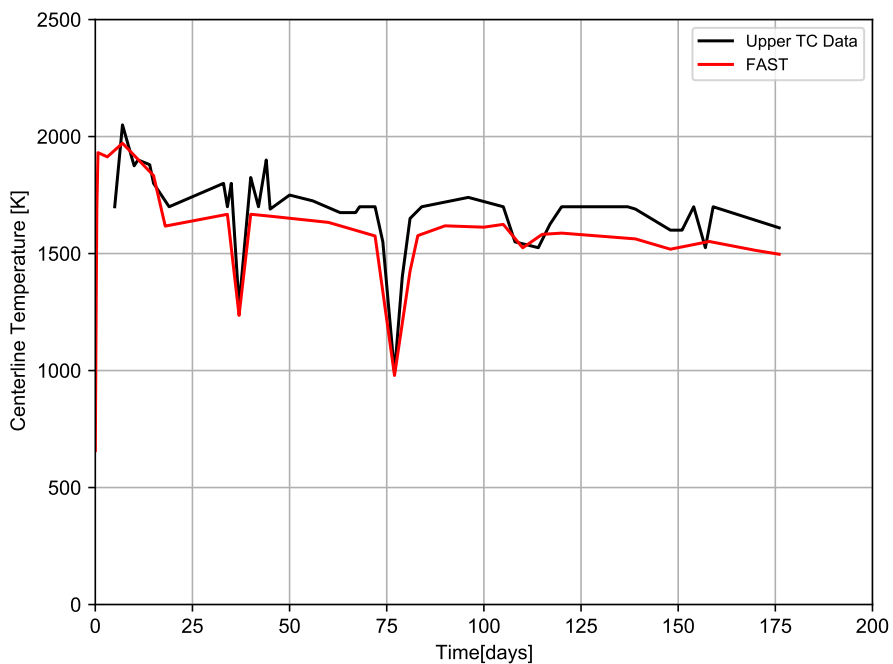
**Figure 3-6.** Measured and predicted centerline temperature for IFA-513 rod 1 UO<sub>2</sub> upper thermocouple (burnup=10 [GWd/MTU], as-fabricated radial gap=108 [ $\mu$ m])



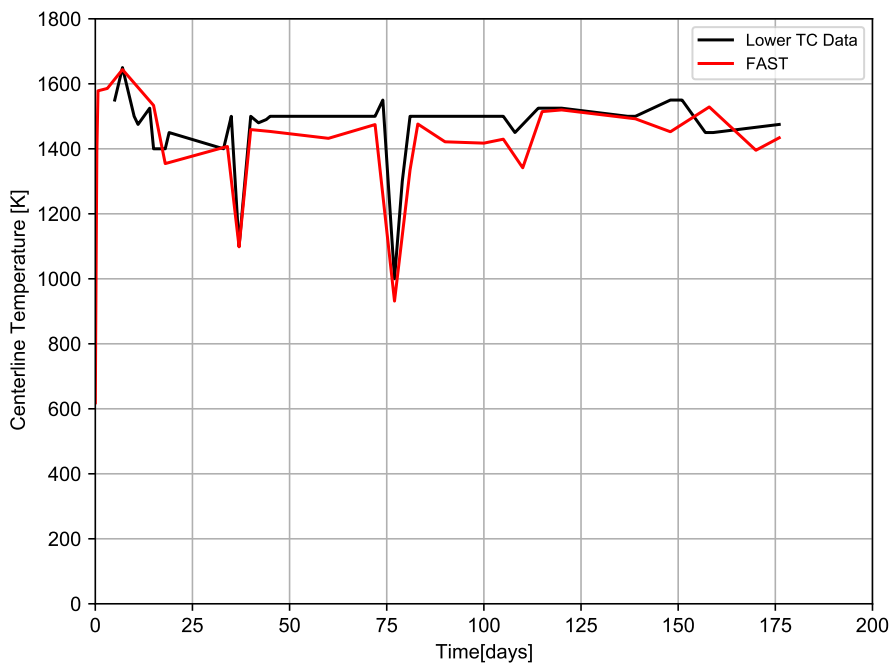
**Figure 3-7.** Measured and predicted centerline temperature for IFA-513 rod 1 UO<sub>2</sub> lower thermocouple (burnup=10 [GWd/MTU], as-fabricated radial gap=108 [ $\mu$ m])

Figures 3-9 and 3-8 show the measured and predicted centerline temperature for IFA-513r6. These

figures contain data from the upper and lower thermocouples and show reasonable agreement between the FAST predictions and the data.



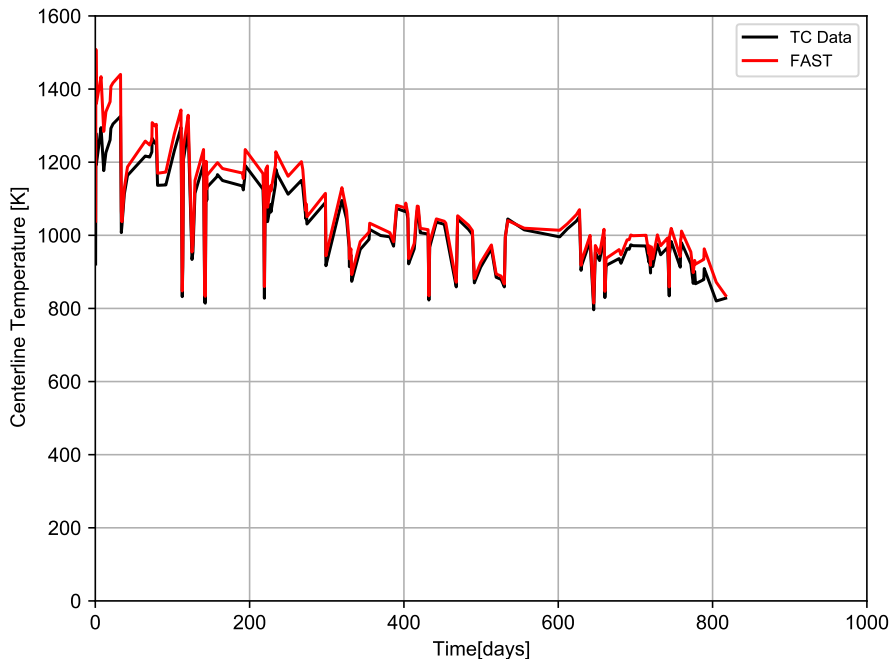
**Figure 3-8.** Measured and predicted centerline temperature for IFA-513 rod 6 UO<sub>2</sub> upper thermocouple (burnup=10 [GWd/MTU], as-fabricated radial gap=108 [ $\mu$ m])



**Figure 3-9.** Measured and predicted centerline temperature for IFA-513 rod 6 UO<sub>2</sub> lower thermocouple (burnup=10 [GWd/MTU], as-fabricated radial gap=108 [ $\mu$ m])

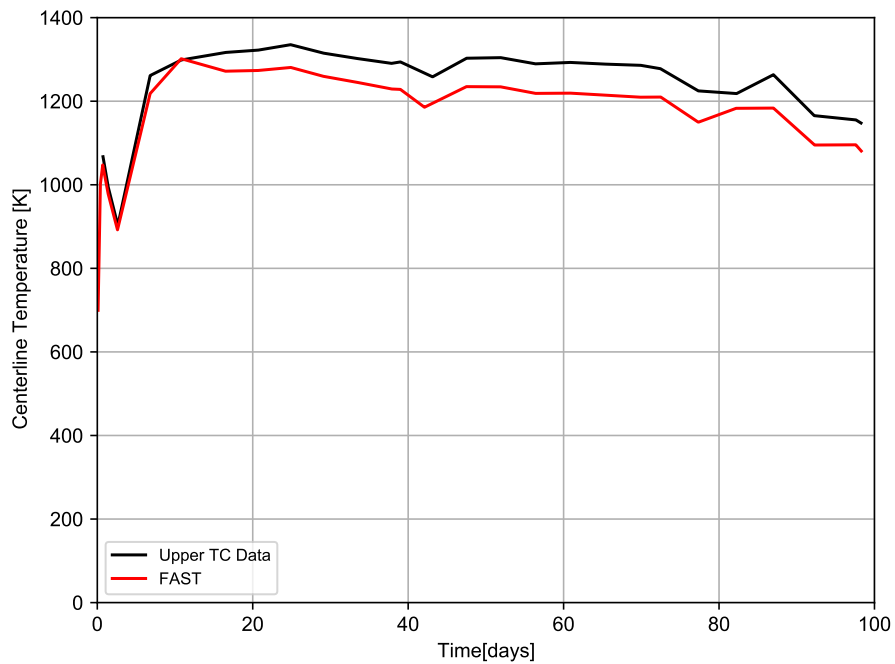


Figure 3-10 shows the measured and predicted centerline temperature for IFA-562r18. This figure contains rod axial-averaged temperature data from the expansion thermometer. This figure shows excellent agreement between the FAST predictions and the data.



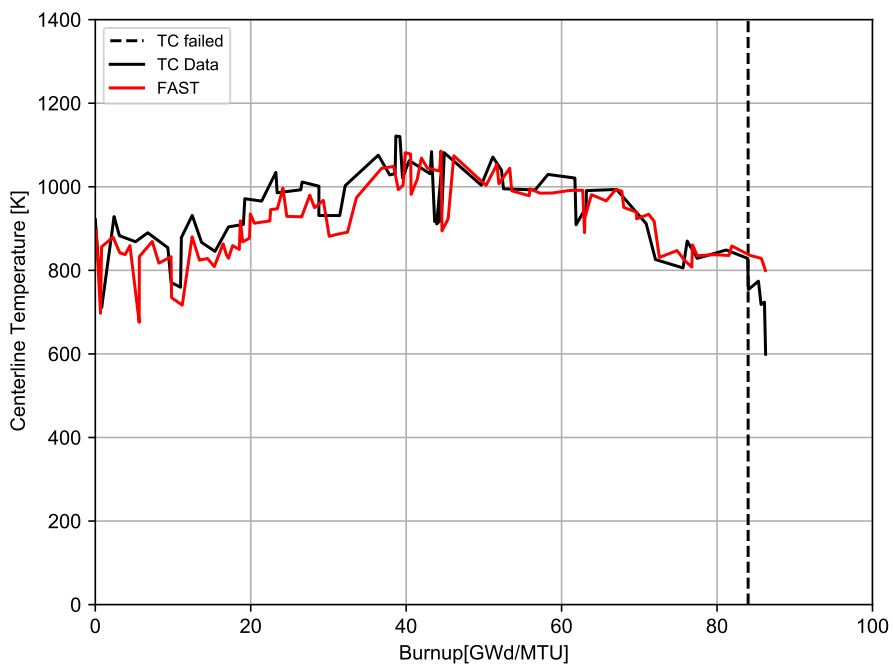
**Figure 3-10.** Measured and predicted rod-average centerline temperature for IFA-562 rod 18 UO<sub>2</sub> (burnup = 76 [GWd/MTU], as-fabricated radial gap = 50 [ $\mu$ m])

Figure 3-11 shows the measured and predicted centerline temperature for IFA-597r8. This rod was refabricated from a commercial rod that was irradiated to 68 [GWd/MTU]. This figure contains upper thermocouple data and shows reasonable agreement between the FAST predictions and the data ( $\pm 75$  [K], 6% relative).

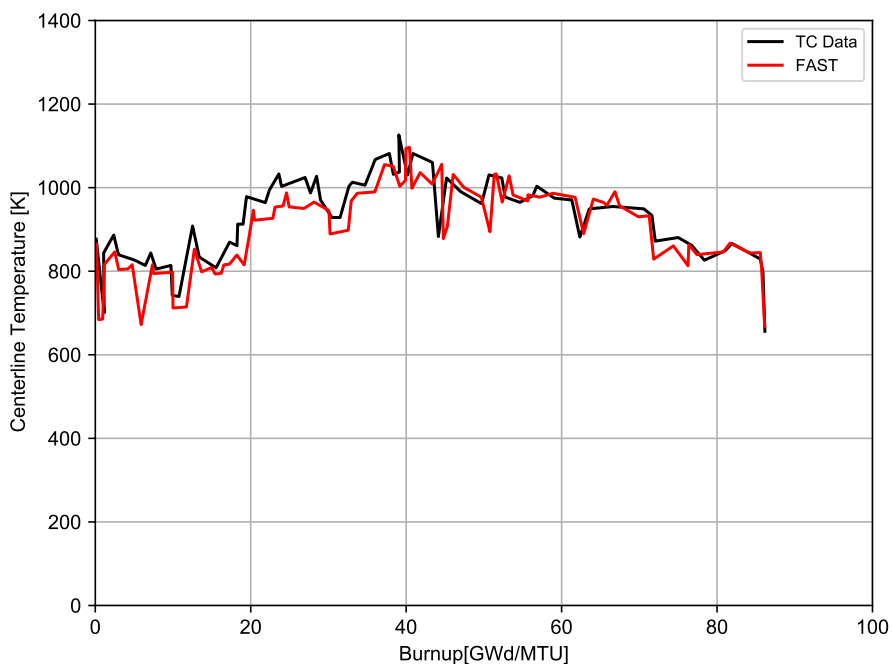


**Figure 3-11.** Measured and predicted centerline temperature for IFA-597 rod 8 (starting burnup = 68 [GWd/MTU], ending burnup=71 [GWd/MTU], as-fabricated radial gap=105 [ $\mu$ m])

Figures 3-12 and 3-13 show the measured and predicted centerline temperature for IFA-515.10 rods A1 and B1. These figures contain upper thermocouple data and show reasonable agreement between the FAST predictions and the data ( $\pm 50$  [K], 6% relative).



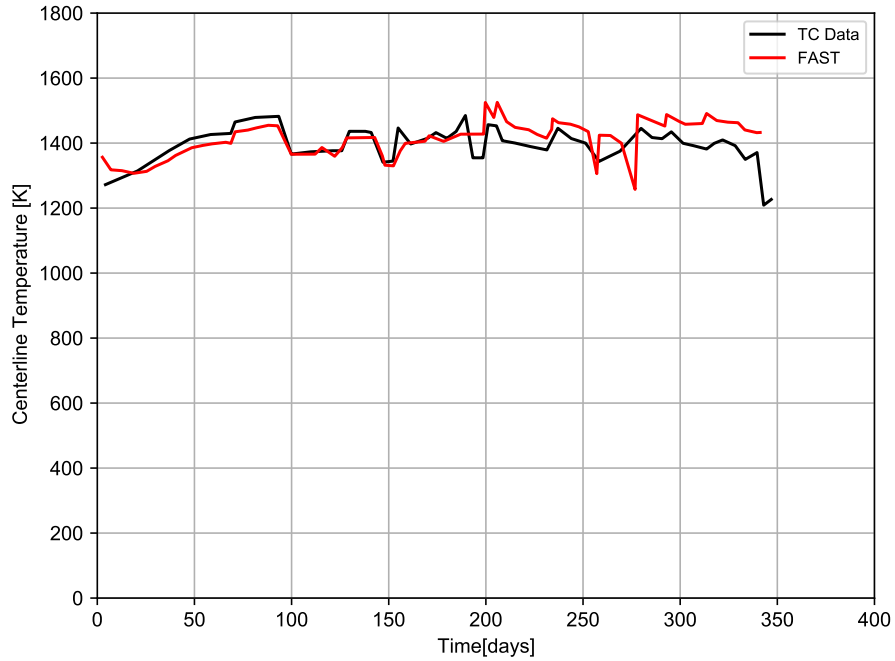
**Figure 3-12.** Measured and predicted centerline temperature for IFA-515.10 rod A1 ( $UO_2$ ) (burnup = 80 [GWd/MTU], as-fabricated radial gap=25 [ $\mu m$ ])



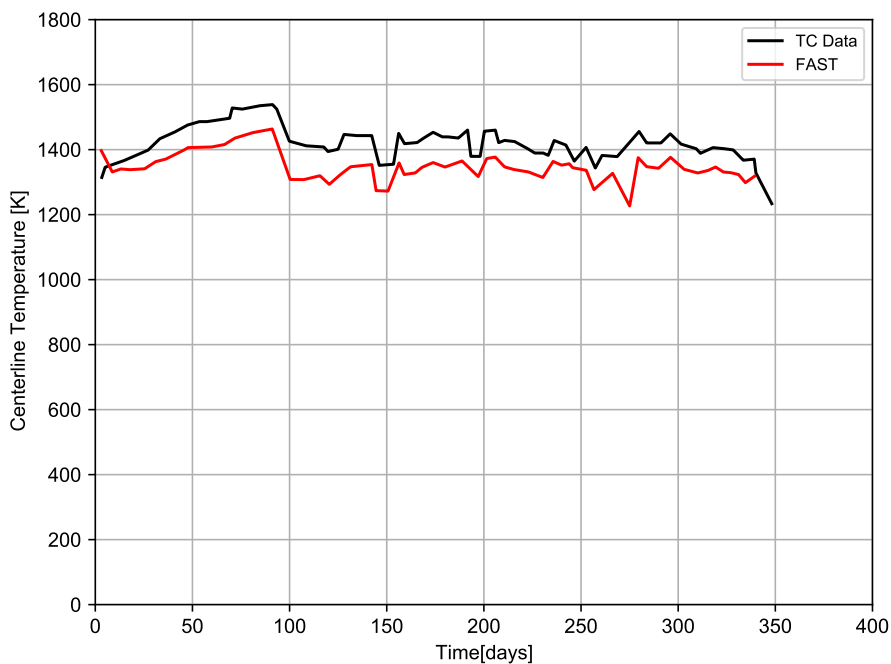
**Figure 3-13.** Measured and predicted centerline temperature for IFA-515.10 rod B1 ( $UO_2$ ) (burnup = 80 [GWd/MTU], as-fabricated radial gap = 25 [ $\mu m$ ])

Figures 3-14 and 3-15 show the measured and predicted centerline temperature for IFA-681 rods

1 and 5. These figures contain upper thermocouple data (rod 1) and expansion thermometer data (rod 5). These figures show reasonable agreement between the FAST predictions and the data ( $\pm 30$  [K], 2% relative).

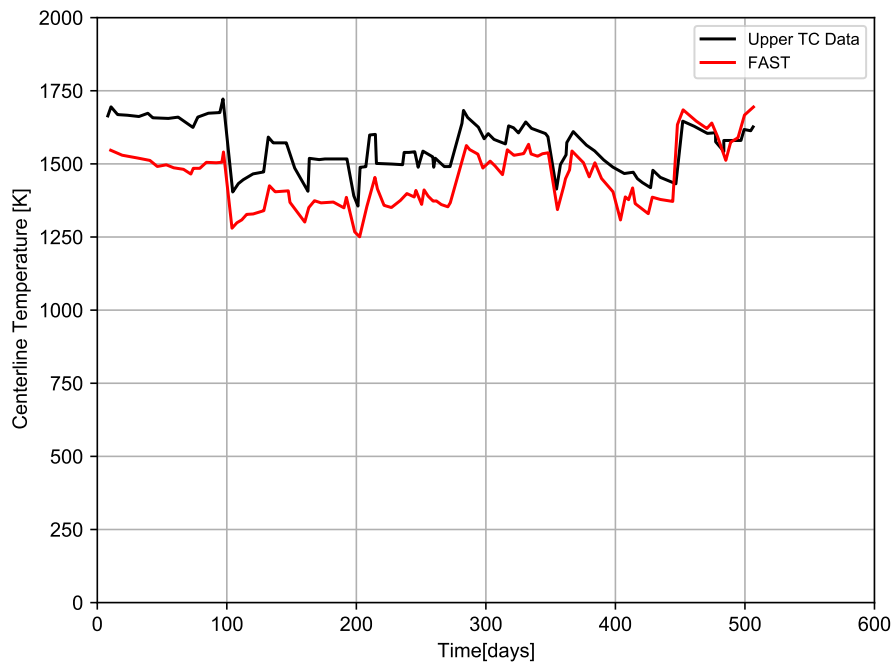


**Figure 3-14.** Measured and predicted centerline temperature for IFA-681 rod 1 UO<sub>2</sub> (burnup = 33 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu$ m])



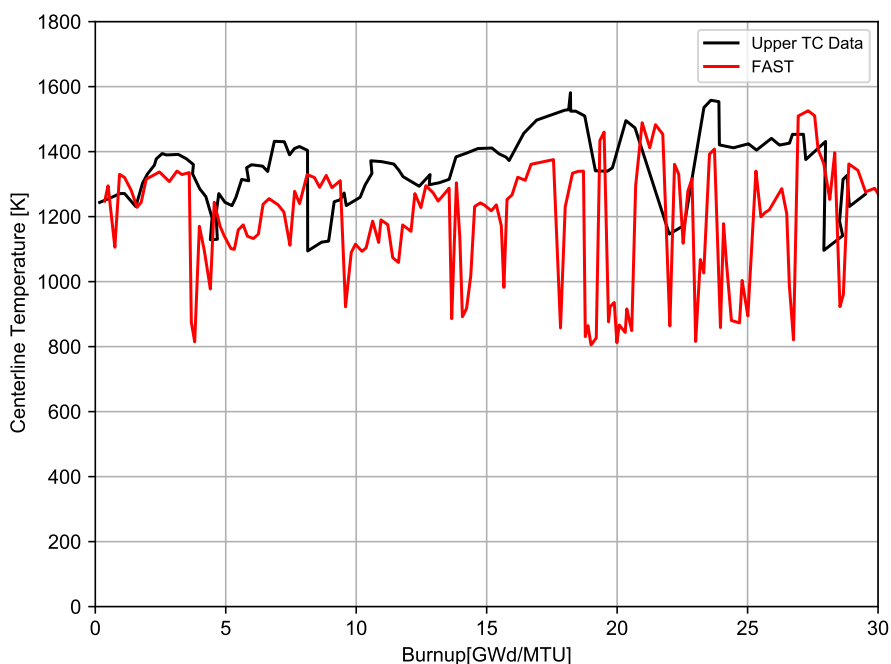
**Figure 3-15.** Measured and predicted centerline temperature for IFA-681 rod 5 UO<sub>2</sub> (burnup = 32 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu$ m])

Figure 3-16 shows the measured and predicted centerline temperature for IFA-677 rod 2. This figure contains upper thermocouple data and shows significant underprediction of the FAST predictions relative to the data at BOL of up to 150 [K] (11% relative). However, by 300 days, the underprediction has been reduced to a more reasonable level of 75 [K] (5% relative) or less. This rod (Figure 3-16) had similar LHGR and burnup and the same gap size as IFA-681 rod 5 (Figure 3-15) but significantly higher fuel centerline temperatures ( $\sim$ 130 [ $^{\circ}$ C], 10% relative) at low burnups.



**Figure 3-16.** Measured and predicted centerline temperature for IFA-677.1 rod 2  $\text{UO}_2$  (burnup = 32 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu\text{m}$ ])

Figure 3-17 shows the measured and predicted centerline temperature for IFA-558 rod 6. This figure contains upper thermocouple data and shows reasonable agreement between the FAST predictions and the data ( $\pm 50\text{-}75$  [K], 4-6% relative), except at burnups between 25.5 and 28 [GWd/MTU], where temperatures are underpredicted by up to 120 [K] (10% relative) but then start to provide good agreement at 29 [GWd/MTU].



**Figure 3-17.** Measured and predicted centerline temperature for IFA-558 rod 6 UO<sub>2</sub> (burnup = 41 [GWd/MTU], as-fabricated radial gap = 95 [ $\mu$ m])

This section demonstrates that FAST continues to provide a best-estimate prediction of centerline temperature for UO<sub>2</sub> rods to within a standard error of 4.7% for recent experimental data (see Figure 3-2). The largest deviation was for IFA-677 rod 2 (Figure 3-16), which shows a 150 [K] (11% relative) underprediction at BOL that decreases to less than 75 [K] (6% relative) by 300 days. All the IFA-677 rods were also slightly underpredicted in the BOL temperature section, perhaps demonstrating a bias in this data, particularly compared with rods of similar power, burnup levels, and gap size that demonstrate better agreement with the code.

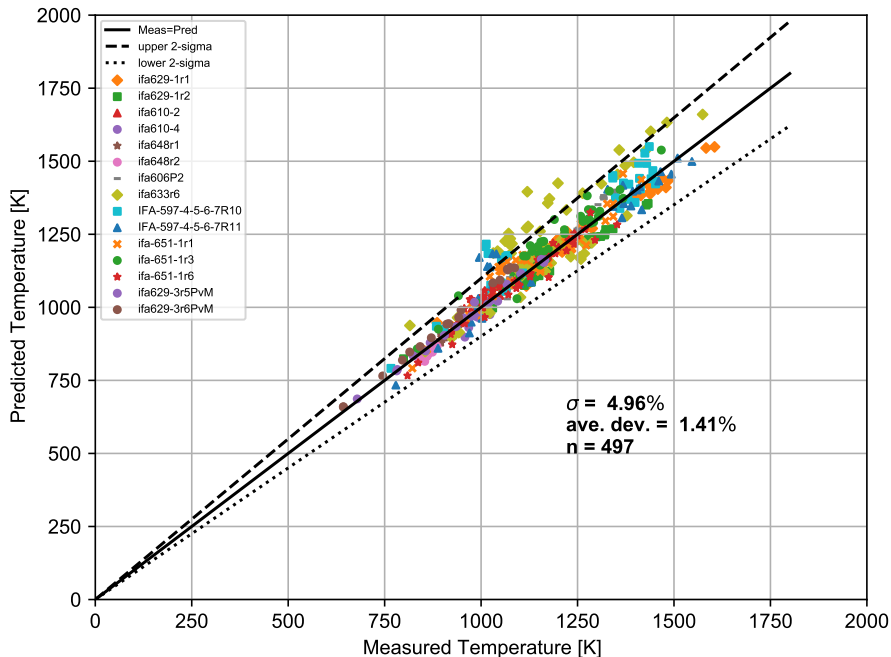
It is noted that in some of these cases the temperatures are predicted well throughout life, while in other cases there is a deviation with time, and in others there is a consistent bias throughout life. The cases with a deviation with time are likely due to a small difference in FGR predictions that affect the calculated centerline temperature or a drift in neutron detectors with time that affects measured rod powers. In some cases, the neutron detectors are recalibrated between reactor cycles such that at a given burnup or time the predicted and measured temperatures begin to agree better or deviate. The cases with a constant bias throughout life are likely due to a bias in the predictions, the reported rod power, or the measured temperature.

### 3.2.2 MOX Centerline Temperature Predictions as a Function of Burnup

FAST predictions have been benchmarked against centerline temperatures taken from eight Halden tests with instrumented fuel assemblies containing 15 MOX fuel rods. The results of these comparisons are provided in this section.

The following figures show measured and predicted fuel centerline temperatures from rods with centerline temperature measurements. Individual rod predictions may demonstrate a systematic error (bias) that may be due to thermocouple decalibration or a systematic error in the power history

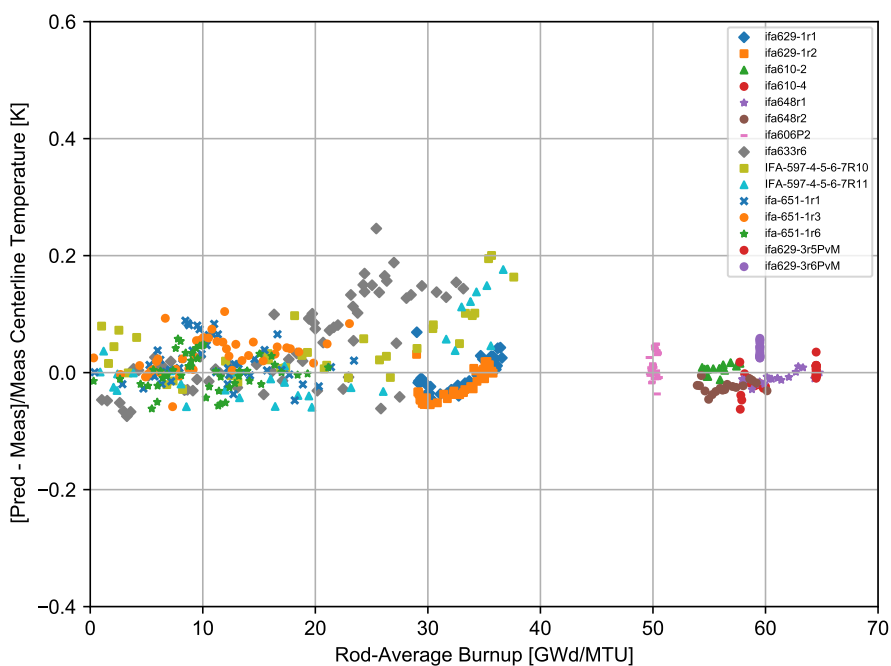
or axial power shape (power at thermocouple location) provided due to decalibration in or with the neutron detectors. However, when all the comparisons are examined, no overall systematic error (bias) is found in the prediction of MOX fuel temperature, as can be seen in Figure 3-18. For all the cases, a standard error of 5.0% on the centerline temperature was calculated.



**Figure 3-18.** Measured and predicted centerline temperature for the MOX assessment cases throughout life

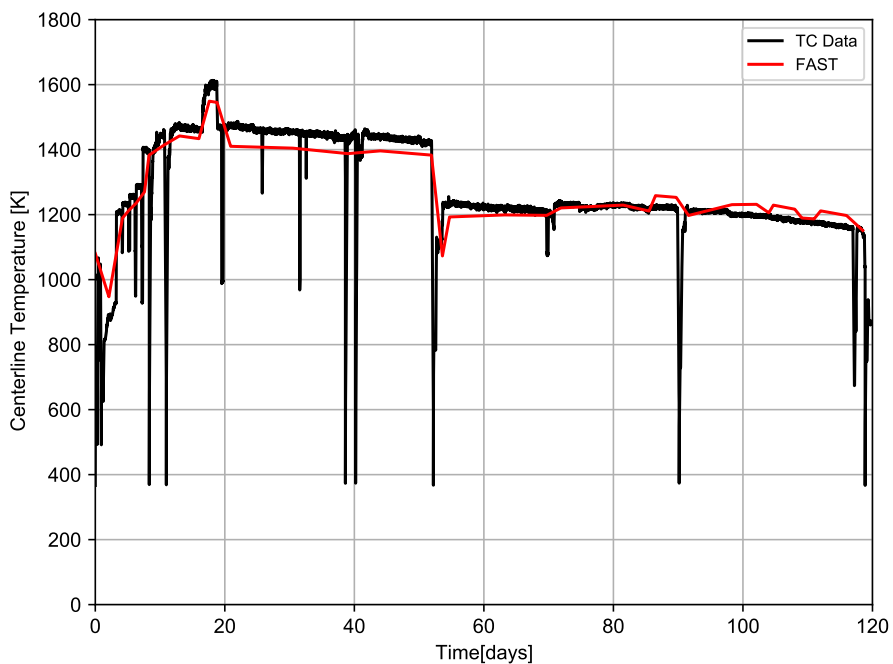
These data are also shown in terms of relative bias in Figure 3-19 as a function of burnup. There appears to be no systematic bias in the predictions with increasing burnup.



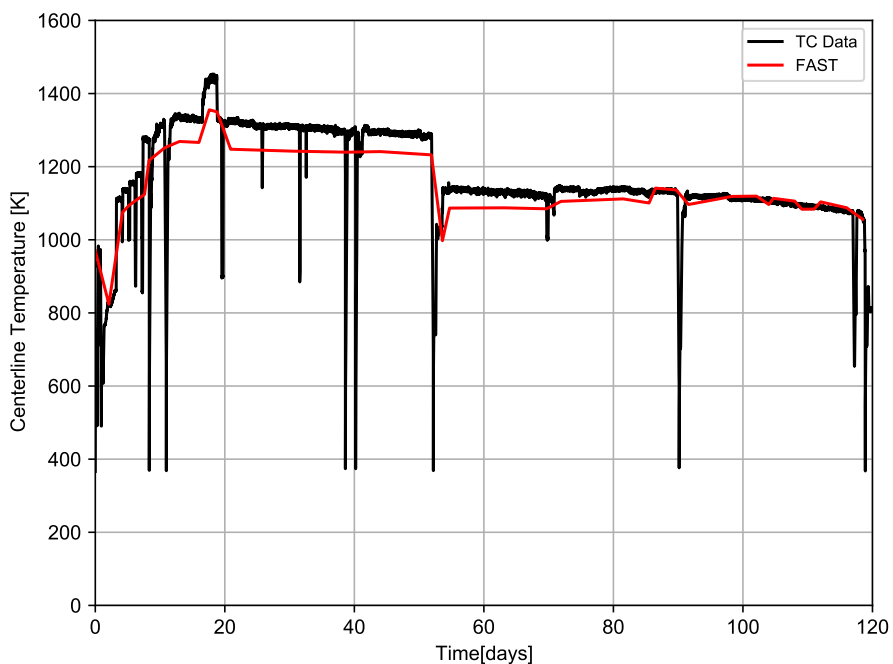


**Figure 3-19.** Predicted minus measured divided by measured centerline temperature for the MOX assessment cases as a function of burnup

Figures 3-20 and 3-21 show the measured and predicted centerline temperatures for IFA-629.1 rods 1 and 2. These figures show good agreement between the FAST predictions and the data. The slight offset during parts of the irradiation could be due to power or thermocouple calibration changes at the end of each cycle.

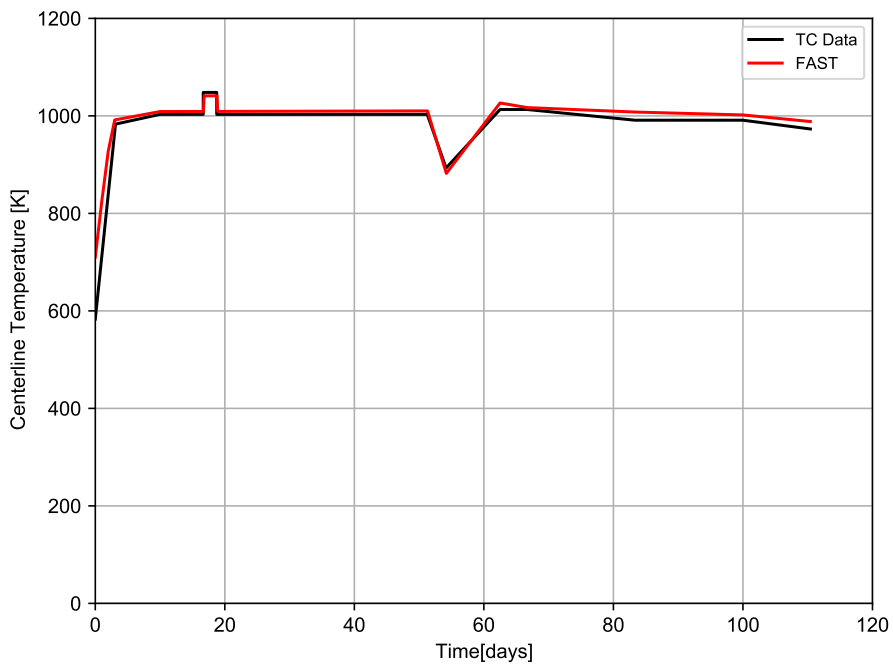


**Figure 3-20.** Measured and predicted centerline temperature for IFA-629.1 rod 1 (MOX) (starting burnup = 27 [GWd/MTU], ending burnup=33 [GWd/MTU], asfabricated radial gap = 84 [ $\mu\text{m}$ ])

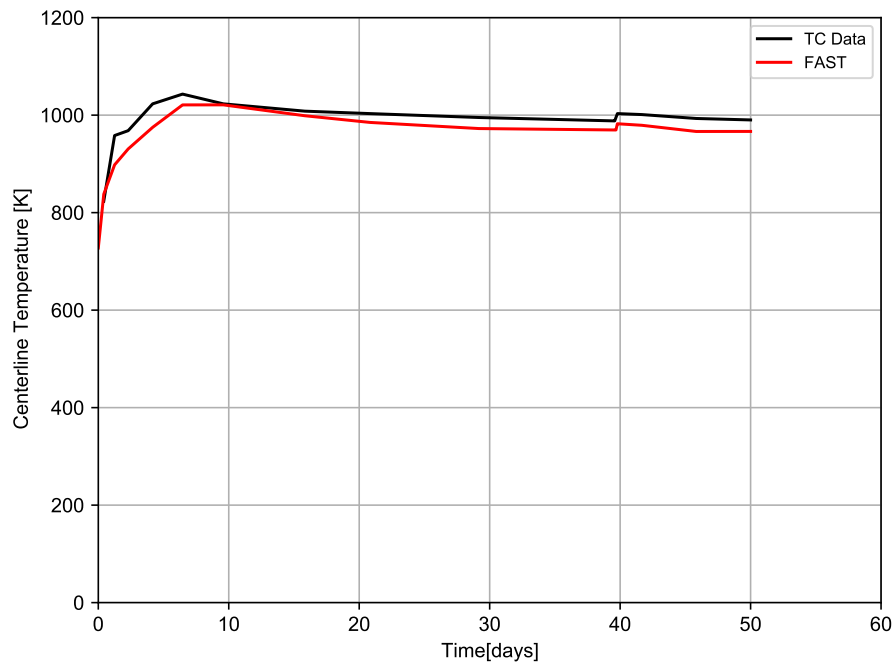


**Figure 3-21.** Measured and predicted centerline temperature for IFA-629.1 rod 2 (starting burnup = 29 [GWd/MTU], ending burnup = 40 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

Figures 3-22 and 3-23 show the measured and predicted centerline temperature for IFA-610.2 and IFA-610.4. These figures show excellent agreement between the FAST predictions and the data.

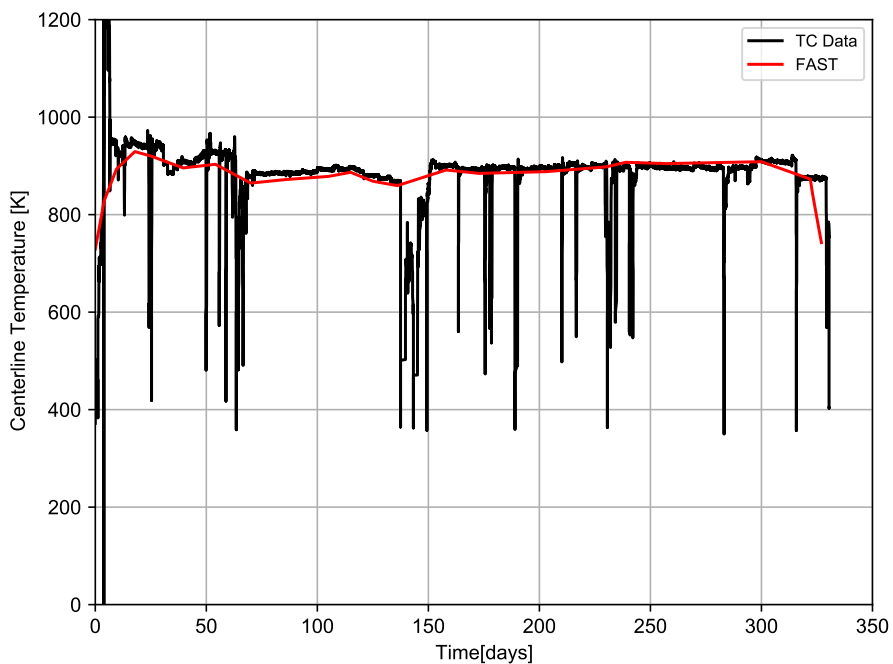


**Figure 3-22.** Measured and predicted centerline temperature for IFA-610.2 (MOX) (starting burnup = 55 [GWd/MTU], ending burnup = 56 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

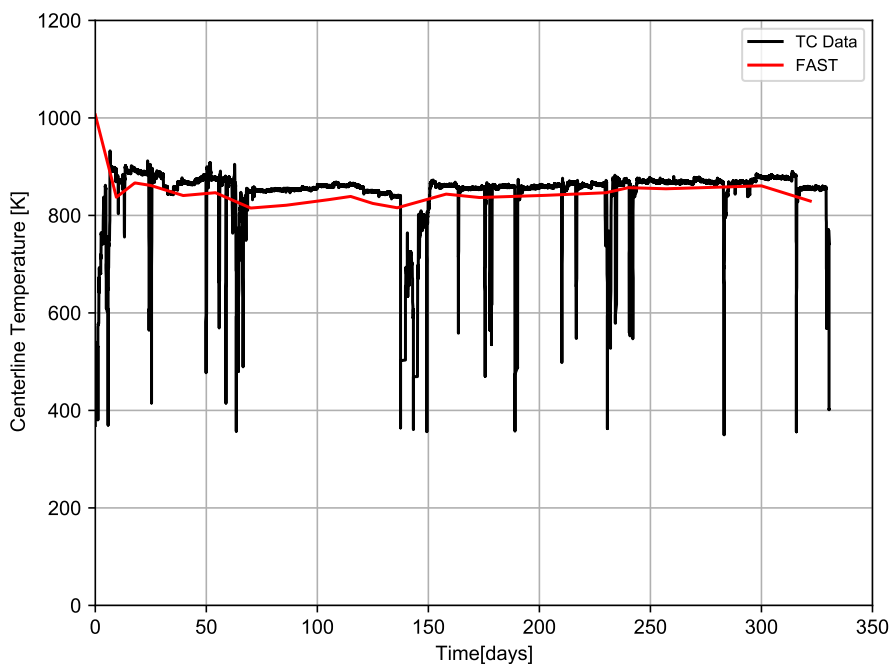


**Figure 3-23.** Measured and predicted centerline temperature for IFA-610.4 (MOX) (starting burnup = 56 [GWd/MTU], ending burnup = 57 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

Figures 3-24 and 3-25 show the measured and predicted centerline temperature for IFA-648.1 rods 1 and 2. These figures show excellent agreement between the FAST predictions and the data.

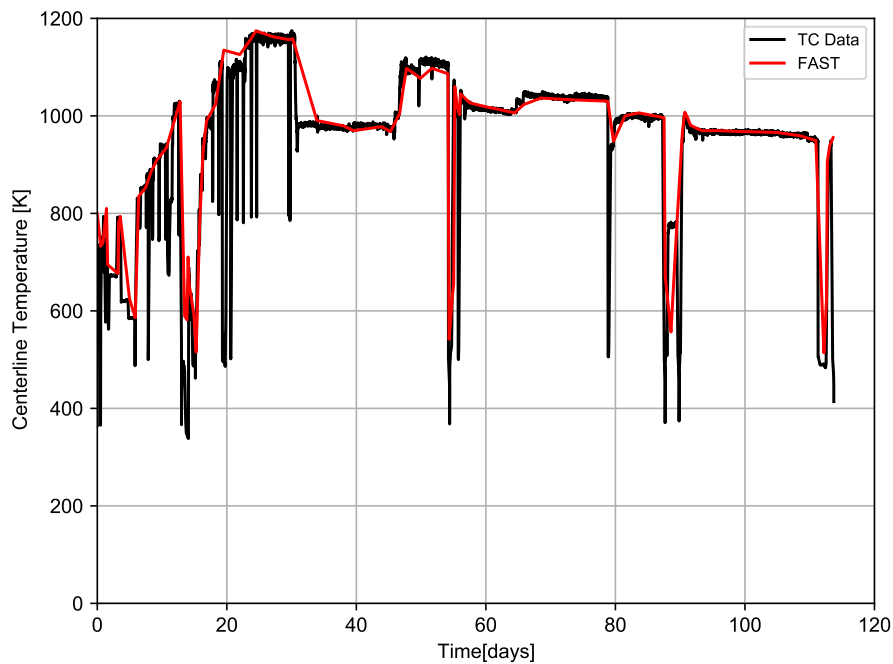


**Figure 3-24.** Measured and predicted centerline temperature for IFA-648.1 rod 1 (MOX) (starting burnup = 55 [GWd/MTU], ending burnup = 62 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

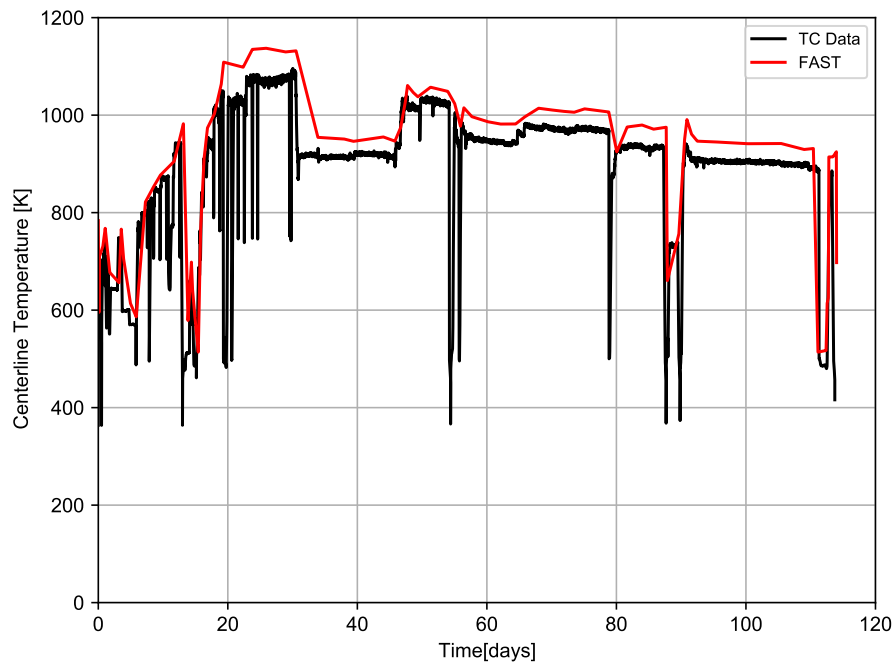


**Figure 3-25.** Measured and predicted centerline temperature for IFA-648.1 rod 2 (MOX) (starting burnup = 55 [GWd/MTU], ending burnup = 62 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

Figures 3-26 and 3-27 show the measured and predicted centerline temperature for IFA-629.3 rods 5 and 6. These figures show excellent agreement between the FAST predictions and the data.

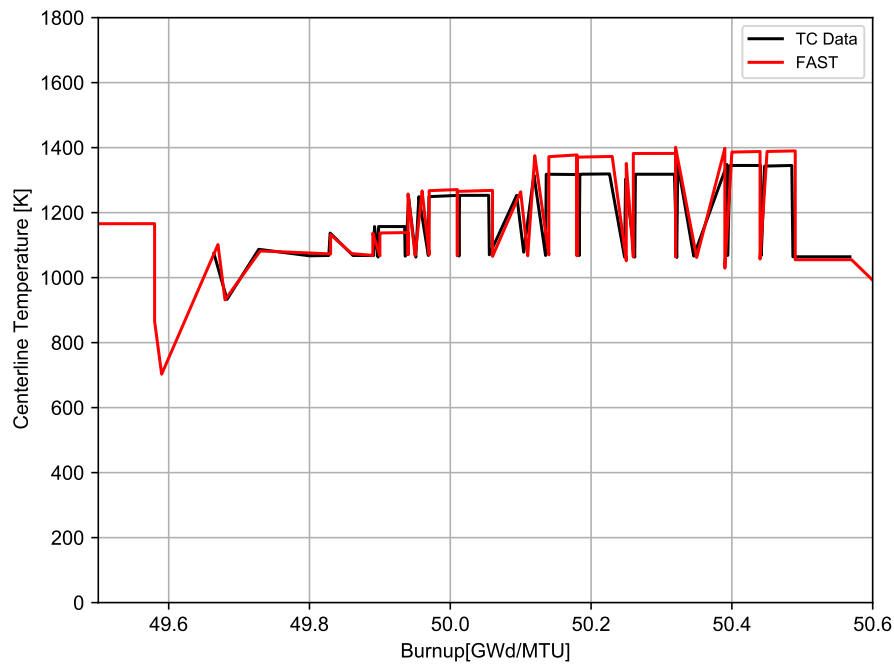


**Figure 3-26.** Measured and predicted centerline temperature for IFA-629.3 rod 5 (MOX) (starting burnup = 62 [GWd/MTU], ending burnup = 72 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])



**Figure 3-27.** Measured and predicted centerline temperature for IFA-629.3 rod 6 (MOX) (starting burnup = 62 [GWd/MTU], ending burnup = 68 [GWd/MTU], as-fabricated radial gap = 84 [ $\mu\text{m}$ ])

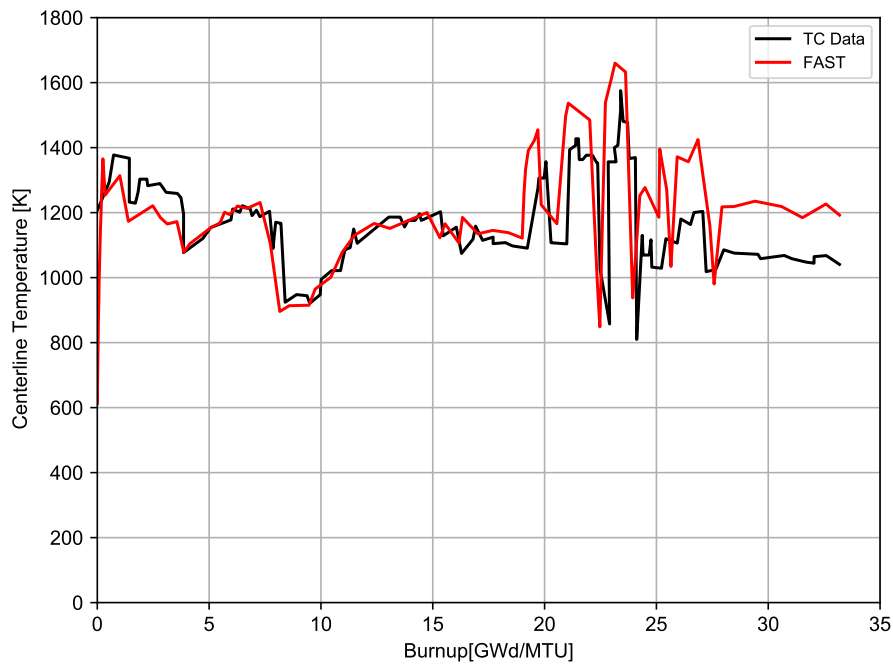
Figure 3-28 shows the measured and predicted centerline temperature for IFA-606 Phase 2. This figure shows reasonable agreement between the FAST predictions and the data (within  $\pm 75$  [K], 7% relative).



**Figure 3-28.** Measured and predicted centerline temperature for IFA-606 Phase 2 (MOX) (starting burnup = 49 [GWd/MTU], as-fabricated radial gap = 94 [ $\mu\text{m}$ ])

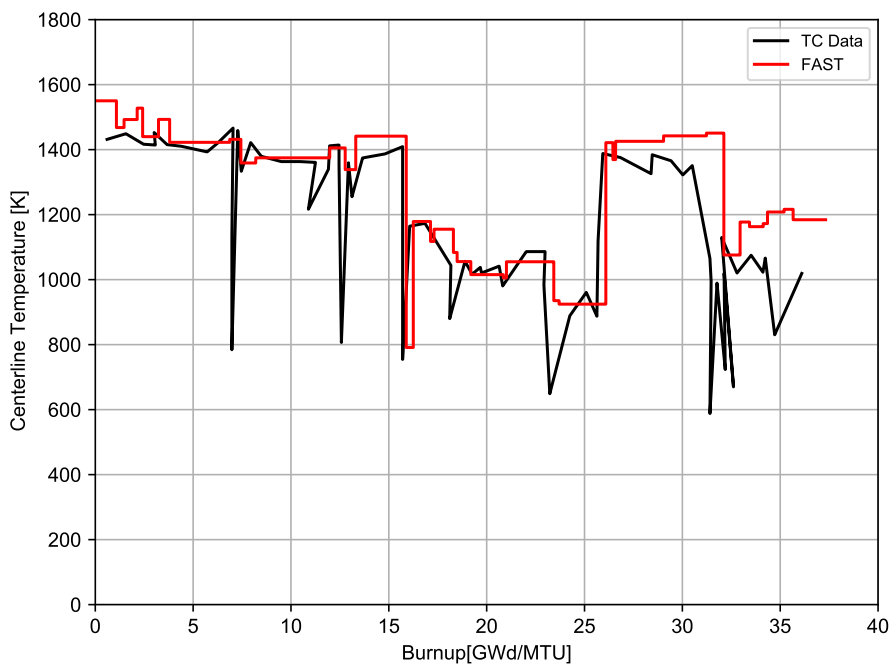
Figure 3-29 shows the measured and predicted centerline temperature for IFA-633-1 rod 6. This figure shows reasonable agreement between the FAST predictions and the data (within  $\pm 75$  [K], 5% relative) until about 26 [GWd/MTU], when FAST overpredicts the data by about 125 to 150K (13% relative). This may be because FAST overpredicts the FGR (measured FGR=6% , predicted=13% ) for this rod, which will lead to increased fuel ratures.



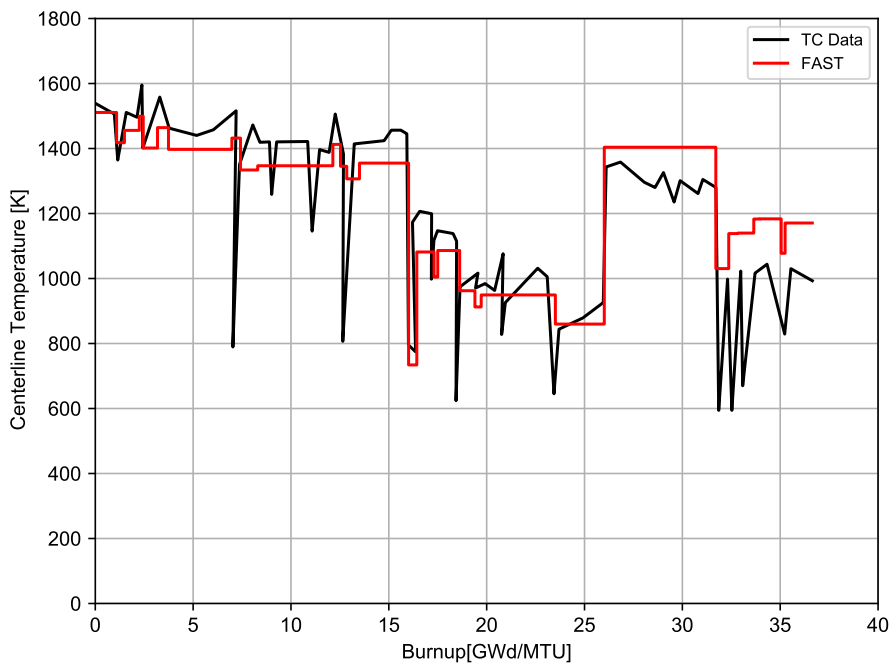


**Figure 3-29.** Measured and predicted centerline temperature for IFA-633-1 rod 6 (MOX) (burnup = 32 [GWd/MTU], as-fabricated radial gap= 104 [ $\mu\text{m}$ ])

Figures 3-30 and 3-31 show the measured and predicted centerline temperature for IFA-597.4, .5, .6, .7 rods 10 and 11. These figures show excellent agreement between the FAST predictions and the data up to 25 [GWd/MTU], when the code begins to overpredict the data by up to 100 [K] (7% relative).



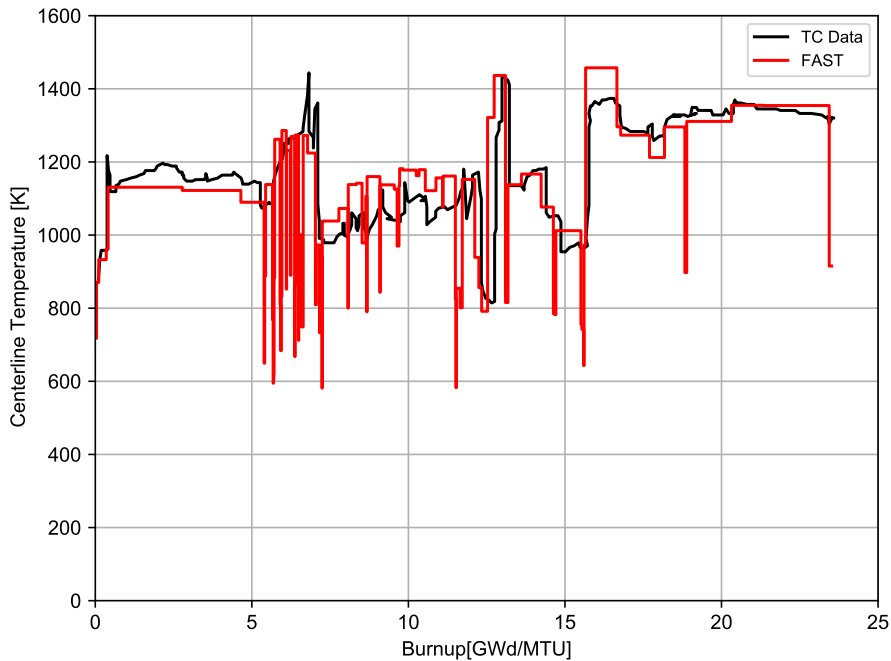
**Figure 3-30.** Measured and predicted centerline temperature for IFA-597.4, .5, .6, .7 rod 10 (MOX) (burnup = 36 [GWd/MTU] as-fabricated radial gap = 95 [ $\mu\text{m}$ ])



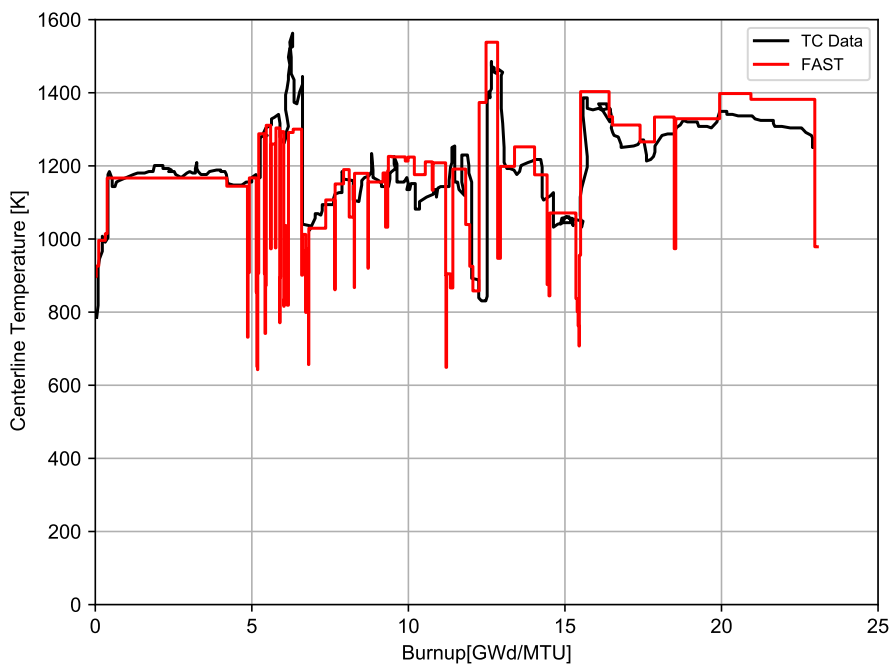
**Figure 3-31.** Measured and predicted centerline temperature for IFA-597.4, .5, .6, .7 rod 11 (MOX) (burnup = 37 [GWd/MTU] as-fabricated radial gap = 95 [ $\mu\text{m}$ ])

Figures 3-32, 3-33, and 3-34 show the measured and predicted centerline temperature for IFA-

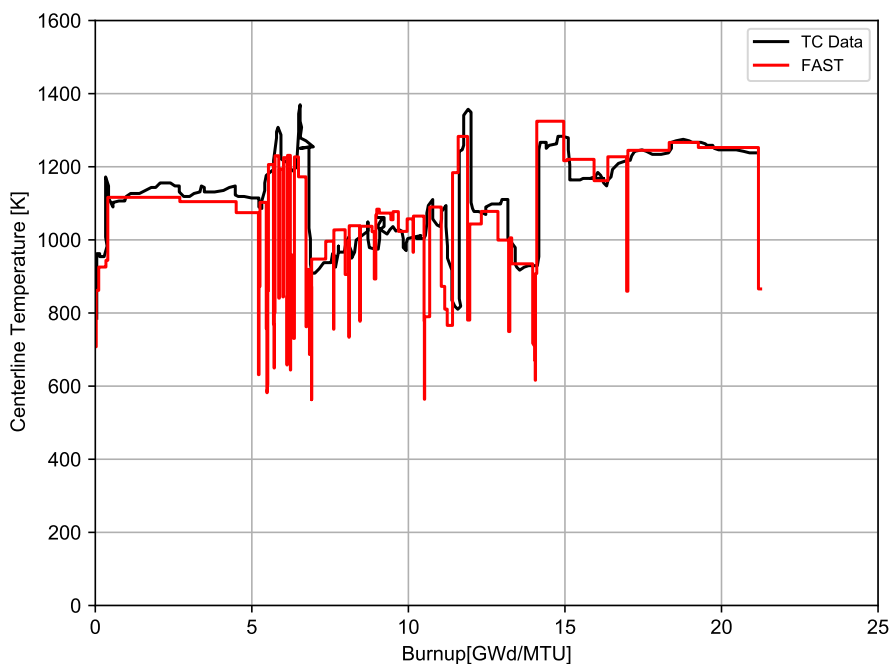
651.1 rods 1, 3, and 6. These figures show excellent agreement between the FAST predictions and the data from rods 1 and 6 that were instrumented with centerline thermocouple, and reasonable agreement ( $\pm 50$  [K], 5% relative) with the data from rod 3 that was instrumented with an expansion thermometer.



**Figure 3-32.** Measured and predicted centerline temperature for IFA-651.1 rod 1 (MOX) (burnup = 22 [GWd/MTU] as-fabricated radial gap = 79 [ $\mu\text{m}$ ])



**Figure 3-33.** Measured and predicted centerline temperature for IFA-651.1 rod 3 (MOX) (burnup = 22 [GWd/MTU] as-fabricated radial gap = 79 [ $\mu\text{m}$ ])



**Figure 3-34.** Measured and predicted centerline temperature for IFA-651.1 rod 6 (MOX) (burnup = 20 [GWd/MTU] as-fabricated radial gap = 81 [ $\mu\text{m}$ ])

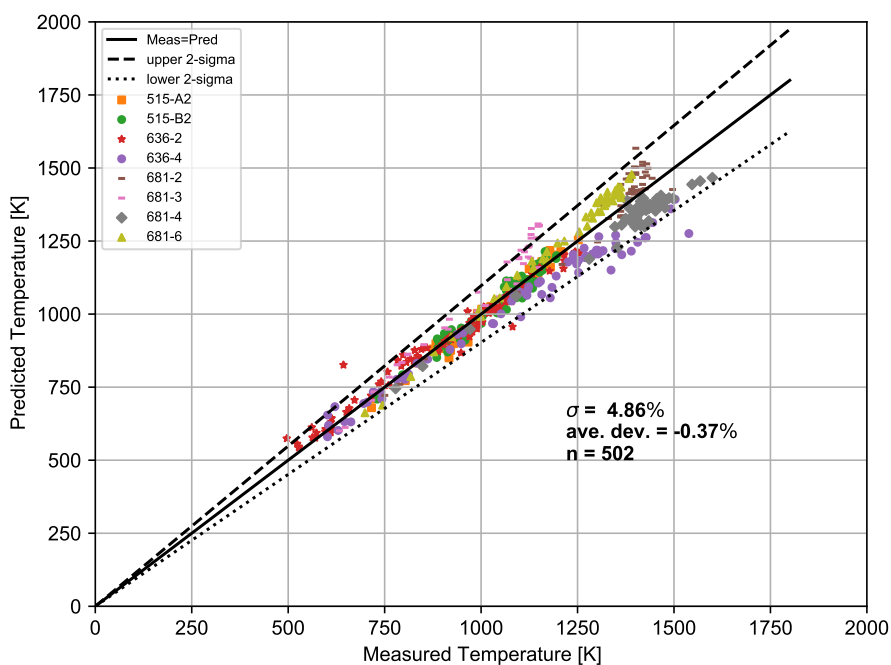
This section demonstrates that FAST continues to provide a best-estimate prediction of centerline

temperature for MOX rods to within a standard error of 4.9% . The largest deviation was for IFA-633.1 rod 6 (Figure 3-29), which shows up to a 150 [K] (13% relative) overprediction at higher burnup. This may be due to overpredicting the FGR for this rod.

### 3.2.3 UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> Centerline Temperature Predictions as a Function of Burnup

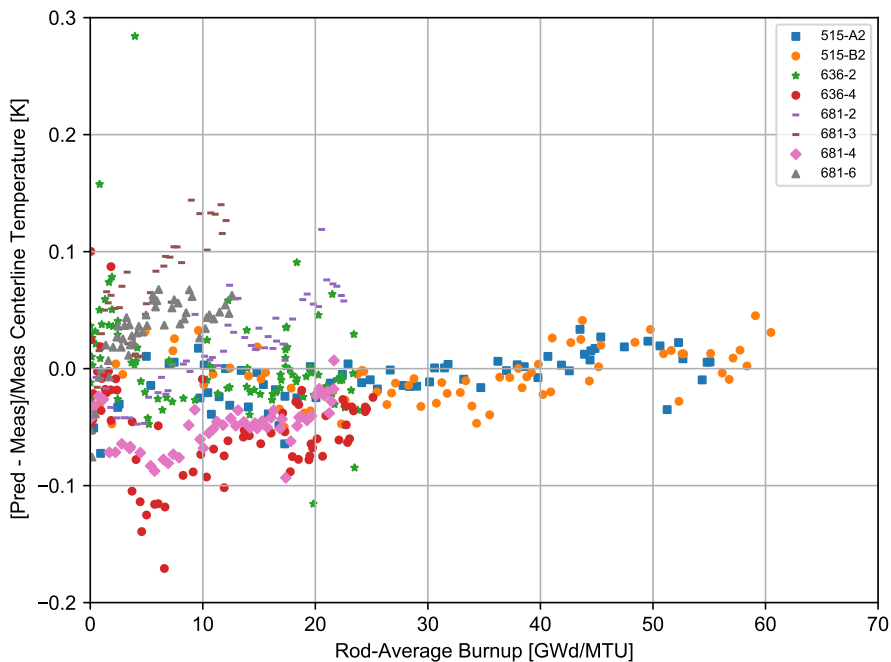
The adjustment for gadolinia in the thermal conductivity model has been assessed against centerline temperature predictions from three instrumented fuel assemblies irradiated at the Halden reactor. The results of these comparisons are provided in this section.

The following figures show measured and predicted fuel centerline temperatures from rods with centerline temperature measurements. Individual rod predictions may demonstrate a systematic error (bias) that may be due to thermocouple decalibration or a systematic error in the power history or axial power shape (power at thermocouple location) provided due to decalibration in or with the neutron detectors with time. However, when all the comparisons are examined, no overall systematic error (bias) is found in the prediction of UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> temperature throughout life, as can be seen in Figure 3-35. For all the cases, a standard error of 4.8% on the centerline temperature was calculated.



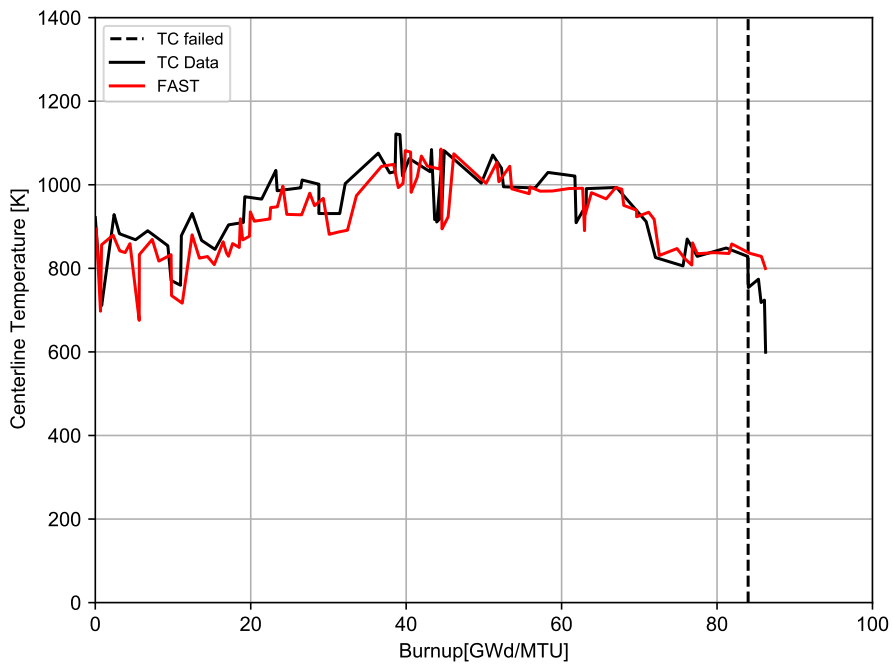
**Figure 3-35.** Measured and predicted centerline temperature for the UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> assessment cases throughout Life

These data are also shown in terms of relative bias in Figure 3-36 as a function of burnup. It can be seen that there appears to be no systematic bias in the predictions with increasing burnup.

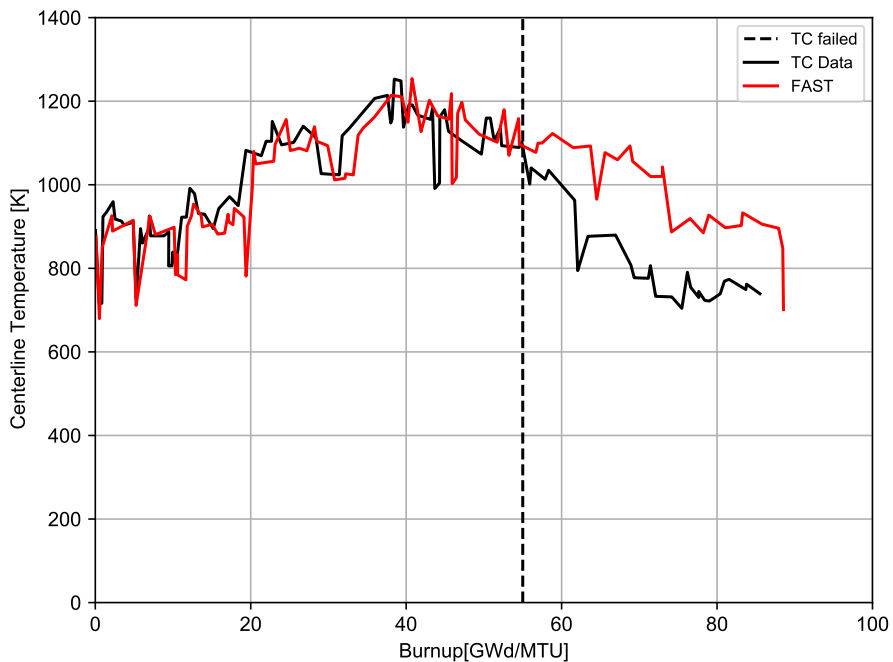


**Figure 3-36.** Predicted minus measured divided by measured centerline temperature for the  $\text{UO}_2\text{Gd}_2\text{O}_3$  assessment cases as a function of burnup

Figures 3-37 and 3-38 show the measured and predicted centerline temperature for IFA-515.10 rods A1, A2, B1, and B2. Rods A1 and B1 (Figures 37(a) and 38(a)) are  $\text{UO}_2$  rods and rods A2 and B2 (Figures 37(b) and 38(b)) are  $\text{UO}_2\text{-Gd}_2\text{O}_3$  rods with depleted gadolinium that did not contain any  $^{155}\text{Gd}$  or  $^{157}\text{Gd}$ . There are two factors that influence the centerline temperature for  $\text{UO}_2\text{-Gd}_2\text{O}_3$  rods relative to  $\text{UO}_2$  rods: 1) TCD due to Gd addition and 2) radial power profile due to the neutron absorption of  $^{155}\text{Gd}$  and  $^{157}\text{Gd}$ . These rods were meant to show the difference only due to the TCD from gadolinia ( $\text{Gd}_2\text{O}_3$ ), not due to the difference in radial power profile. A modified version of FAST that uses the  $\text{UO}_2$  radial power profile model (TUBRNP) for  $\text{UO}_2\text{-Gd}_2\text{O}_3$  rods (A2 and B2) was used to perform these calculations. These figures show that FAST predicts the centerline temperatures for  $\text{UO}_2\text{-Gd}_2\text{O}_3$  rods as well as for  $\text{UO}_2$  rods. In these figures, the vertical line denotes where the thermocouple failed. Although data were reported after this point, it is not valid.

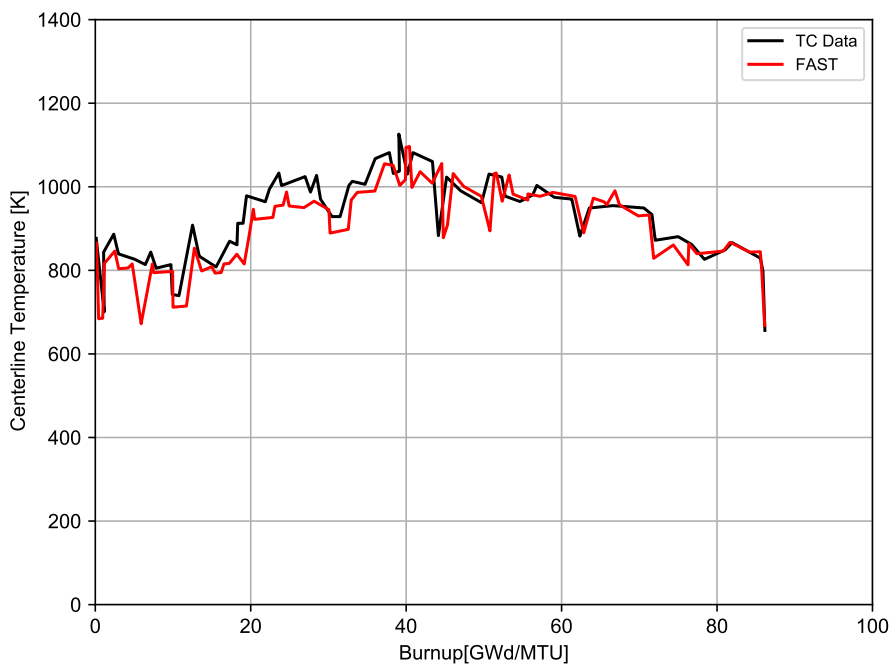


(a) Rod A1

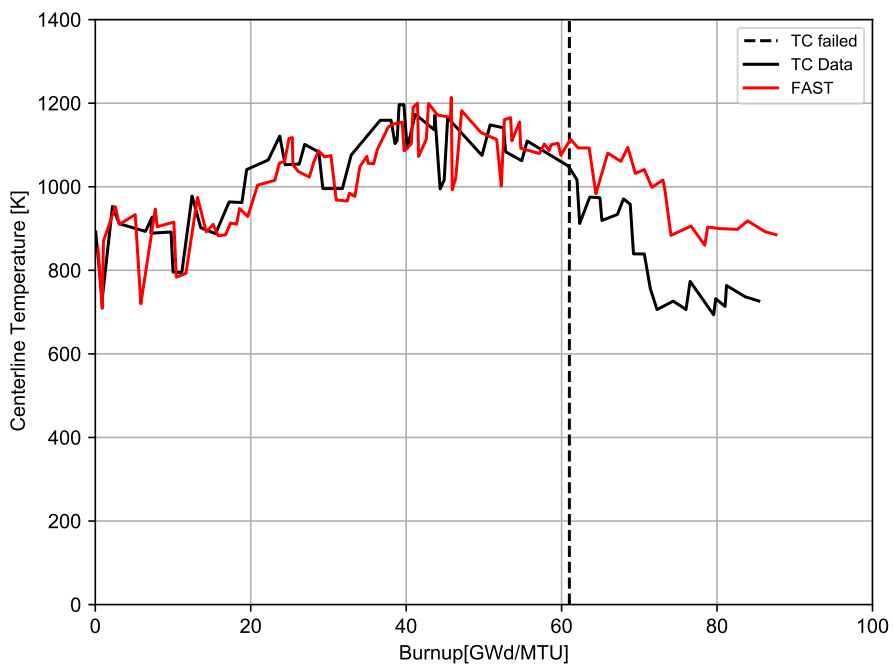


(b) Rod A2

**Figure 3-37.** Measured and predicted centerline temperature for IFA-515.10 rods A1 ( $\text{UO}_2$ ) and A2 ( $\text{UO}_2$ -8%  $\text{Gd}_2\text{O}_3$ ) (burnup=80 [GWd/MTU], as-fabricated radial gap=25 [ $\mu\text{m}$ ])



(a) Rod B1



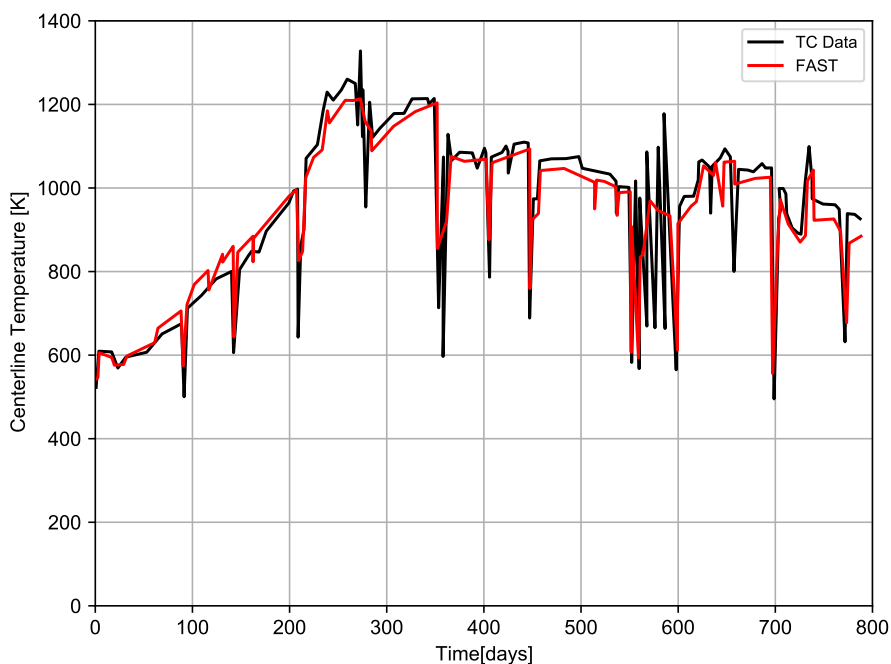
(b) Rod B2

**Figure 3-38.** Measured and predicted centerline temperature for IFA-515.10 rods B1 ( $\text{UO}_2$ ) and B2 ( $\text{UO}_2$ -8%  $\text{Gd}_2\text{O}_3$ ) (burnup=80 [GWd/MTU], as-fabricated radial gap=25 [ $\mu\text{m}$ ])

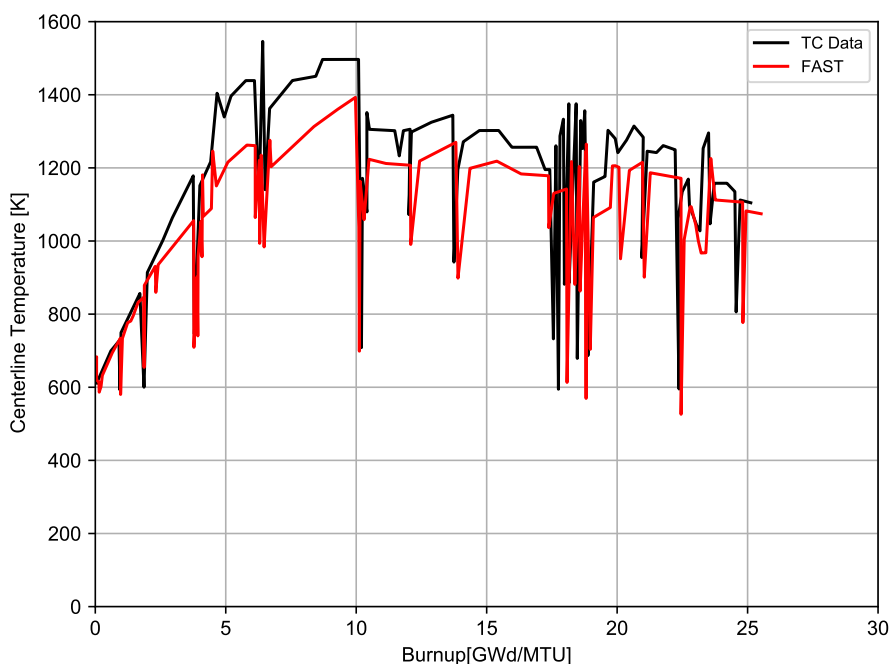
Figures 3-39 and 3-40 show the measured and predicted centerline temperature for IFA-636 rods 2 and 4. These rods contain standard Gd (no Gd depletion like IFA-515.10), so the release version



of FAST could be used. Rod 2 was equipped with a centerline thermocouple, and the data from this thermocouple is shown in Figure 3-39. Rod 4 contains solid pellets, and the data in Figure 3-40 is estimated from rod 2. Because rod 4 does not have a direct measurement of temperature (no thermocouple), there is more uncertainty in the data because this is estimated by Halden using the rod 2 temperature data and correcting for no thermocouple hole. In addition, as the Gd is burning out during the first rise to power, there is a high level of uncertainty on the reported rod power. Because of this, FAST may not predict the centerline temperature well during this period. These figures show excellent agreement between the FAST predictions and the data for rod 2 and significant underprediction (175 [K], 15% relative) between 4 and 10 [GWd/MTU] and reasonable agreement above 10 [GWd/MTU] for rod 4, which has greater uncertainty.



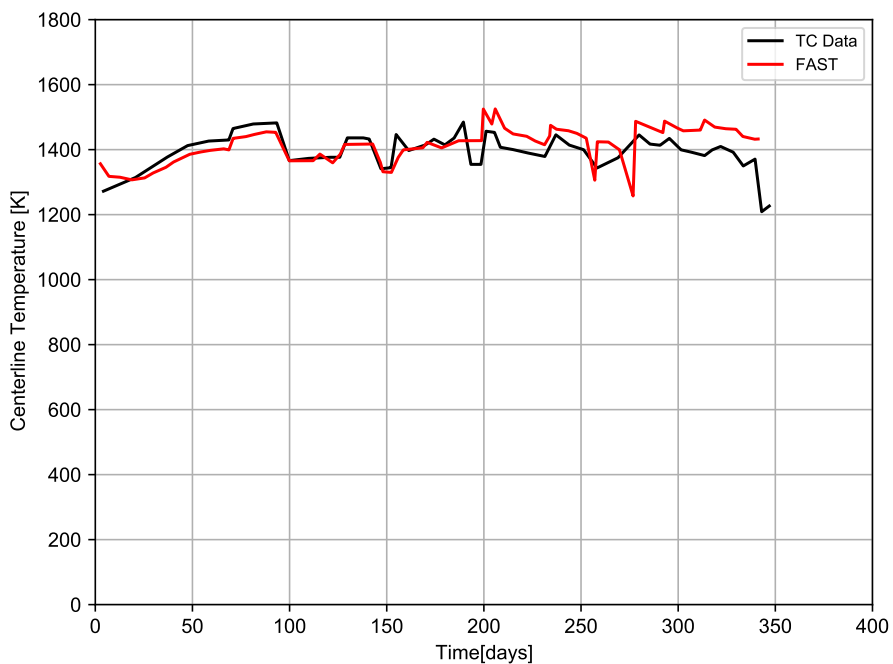
**Figure 3-39.** Measured and predicted centerline temperature for IFA-636 rod 2 ( $\text{UO}_2$ -8%  $\text{Gd}_2\text{O}_3$ ) (burnup=25 [GWd/MTU], as-fabricated radial gap=77 [ $\mu\text{m}$ ])



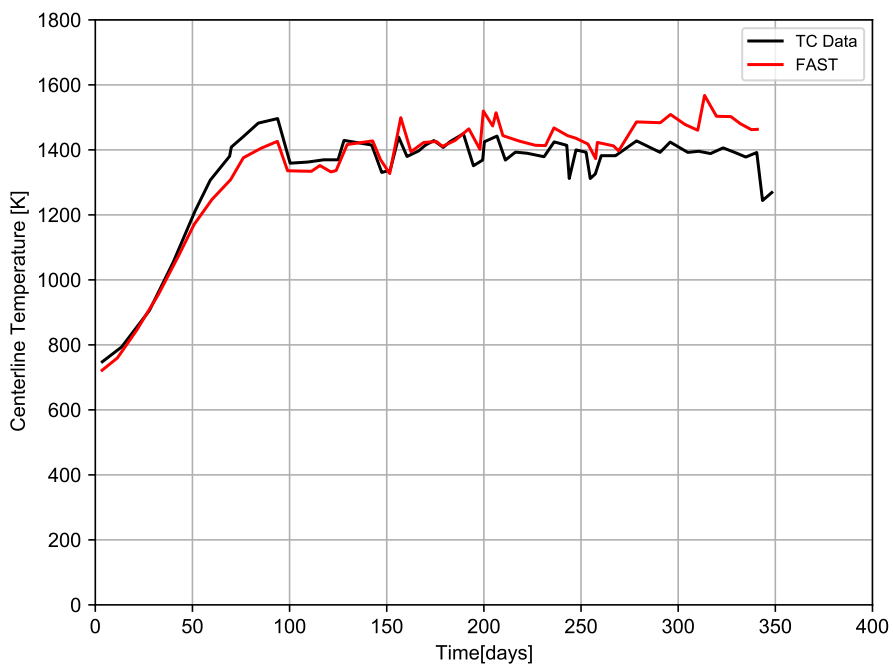
**Figure 3-40.** Measured and predicted centerline temperature for IFA-636 rod 4 ( $\text{UO}_2$ -8%  $\text{Gd}_2\text{O}_3$ ) (burnup = 25 [GWd/MTU], as-fabricated radial gap = 77 [ $\mu\text{m}$ ])

Figures 3-41 through 3-46 show the measured and predicted centerline temperature for IFA-681 rods 1, 2, and 3 with centerline thermocouples and rods 4, 5, and 6 with hollow pellets and expansion thermometers. Rods 1 and 5 are  $\text{UO}_2$  rods; rods 2 and 4 contain standard Gd with 2 wt%  $\text{Gd}_2\text{O}_3$ ; rods 3 and 6 contain standard Gd with 8 wt%  $\text{Gd}_2\text{O}_3$ . Since these rods contain standard Gd, the release version of FAST could be used. During the first rise to power, as the Gd is burning out, there is a high level of uncertainty on the reported rod power. Because of this, FAST may not predict the centerline temperature well during this period. This does not significantly affect future predictions because power levels while the Gd is burning out are low and will not cause significant FGR that will affect future temperature predictions.

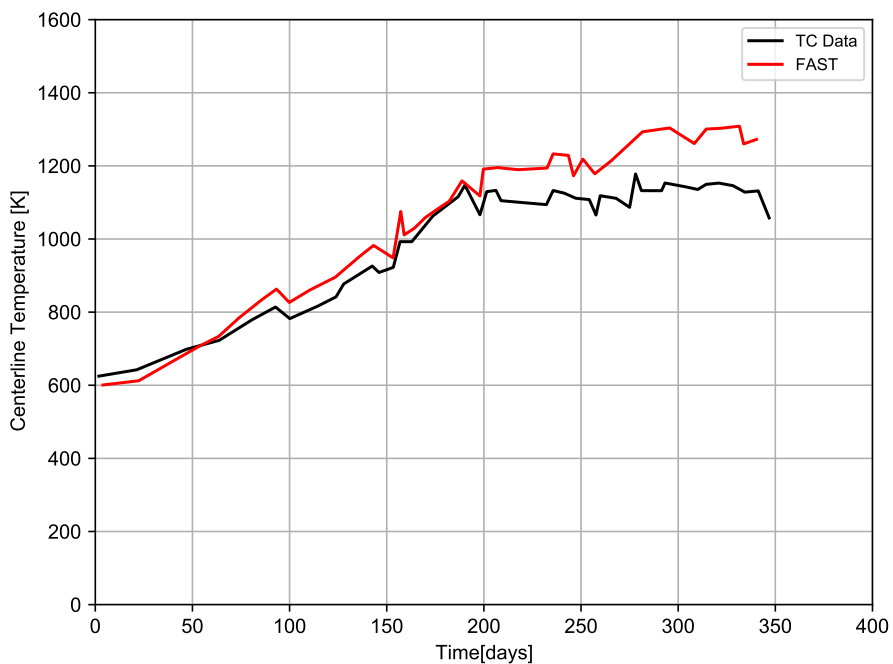
These figures show excellent agreement between the FAST predictions and the data for rod 1 ( $\text{UO}_2$ , Figure 3-41) and 2 (2 wt%  $\text{Gd}_2\text{O}_3$ , Figure 3-42). For rod 3 (8 wt%  $\text{Gd}_2\text{O}_3$ , Figure 3-43), the FAST predictions are in excellent agreement with the data for the first 200 days. After this, FAST overpredicts the data by up to 120 [K] (13% relative). The reason for this is not clear, as both the power and the FAST temperature prediction increase during this time period, but the measured temperature does not increase with increasing power. For the hollow pellet rods, the 2 wt%  $\text{Gd}_2\text{O}_3$  rods (IFA-681 rod 4 in Figure 3-44 and rod 5 in Figure 3-45) is uniformly underpredicted by about 50-90 [K] (4-7% relative) while the 8 wt%  $\text{Gd}_2\text{O}_3$  rod (IFA-681 rod 6, Figure 3-46) is predicted well. These differences are well within the uncertainty of temperature measurement and power levels.



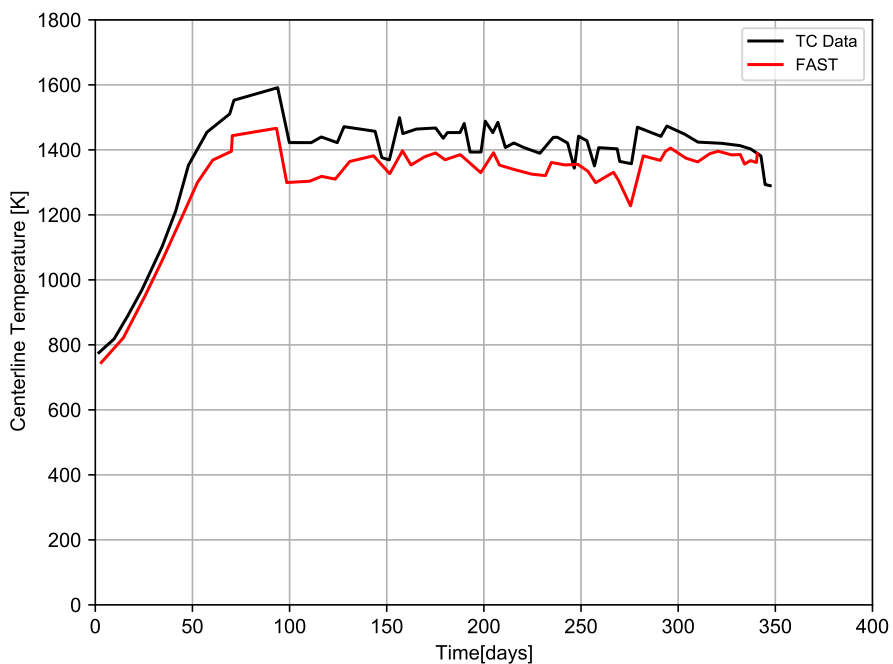
**Figure 3-41.** Measured and predicted centerline temperature for IFA-681 rod 1 ( $\text{UO}_2$ ) (burnup = 24 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu\text{m}$ ])



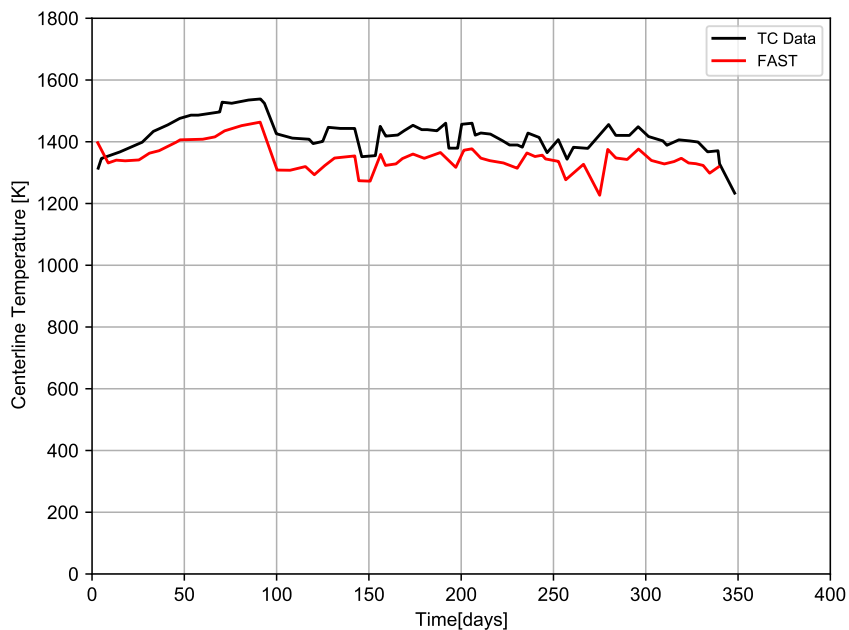
**Figure 3-42.** Measured and predicted centerline temperature for IFA-681 rod 2 ( $\text{UO}_2$ -2%  $\text{Gd}_2\text{O}_3$ ) (burnup = 23 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu\text{m}$ ])



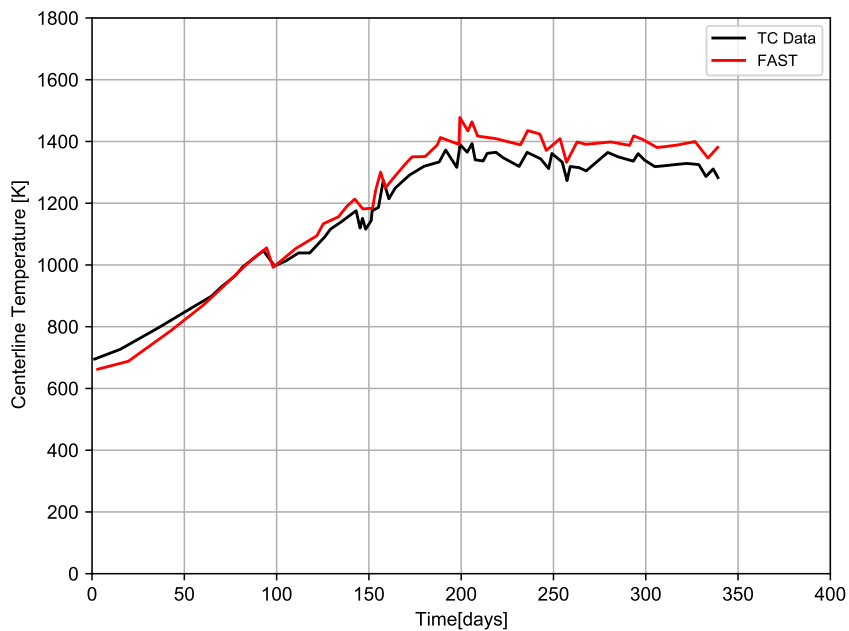
**Figure 3-43.** Measured and predicted centerline temperature for IFA-681 rod 3 ( $\text{UO}_2$ -8%  $\text{Gd}_2\text{O}_3$ ) (burnup = 12 [GWd/MTU], as-fabricated radial gap=85 [ $\mu\text{m}$ ])



**Figure 3-44.** Measured and predicted centerline temperature for IFA-681 rod 4 ( $\text{UO}_2$ -2%  $\text{Gd}_2\text{O}_3$ ) (burnup = 22 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu\text{m}$ ])



**Figure 3-45.** Measured and predicted centerline temperature for IFA-681 rod 5 ( $UO_2$ ) (burnup = 23 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu m$ ])



**Figure 3-46.** Measured and predicted centerline temperature for IFA-681 rod 6 ( $UO_2$ -8%  $Gd_2O_3$ ) (burnup = 13 [GWd/MTU], as-fabricated radial gap = 85 [ $\mu m$ ])

This section demonstrates that FAST continues to provide a best-estimate prediction of centerline temperature for  $UO_2$ - $Gd_2O_3$  rods to within a standard error of 4.8% for recent experimental data.

## 4.0 Fission Gas Release Assessment

### 4.1 Assessment of Steady-State FGR Predictions

An accurate prediction of FGR is important for two reasons: 1) it has a significant impact on the prediction of gap conductance and, therefore, fuel temperatures (e.g., as demonstrated in Section 3.2, an overprediction of FGR can result in an overprediction of fuel temperatures, and the converse is also true), and 2) it is necessary for the calculation of rod internal pressures that affect LOCA analyses and EOL rod pressures. In many cases, for current operating plants, the limits on and analyses of EOL rod pressures determine the LHGR limits for commercial fuel at burnups greater than 30 [GWd/MTU]. In addition, the NRC requires that these EOL rod pressure analyses include bounding normal operation transients (e.g., xenon transients lasting several hours) and AOOs (e.g., overpower transients lasting several minutes to hours). Therefore, the accurate prediction of transient FGR under conditions of power increases above steady-state operation is important for licensing analyses.

The code's ability to predict FGR in  $\text{UO}_2$  fuel has been assessed based on comparisons to FGR data from 23  $\text{UO}_2$  fuel rods with power histories that are relatively steady-state through the rod's irradiation life and 19  $\text{UO}_2$  rods with power bumping (increase in rod power) at EOL to simulate an overpower AOO or normal operational transients. The code's ability to predict FGR in MOX fuel has been assessed based on comparisons to FGR data from 34 MOX fuel rods with power histories that are relatively steady-state through the rod's irradiation life and 8 MOX rods with power bumping (increase in rod power) at EOL to simulate an overpower AOO or normal operational transients. The fuel rods with greater than 5% FGR were selected because the limiting rods in terms of EOL rod pressure in today's plants (particularly for power uprated plants) have releases above 10% FGR.

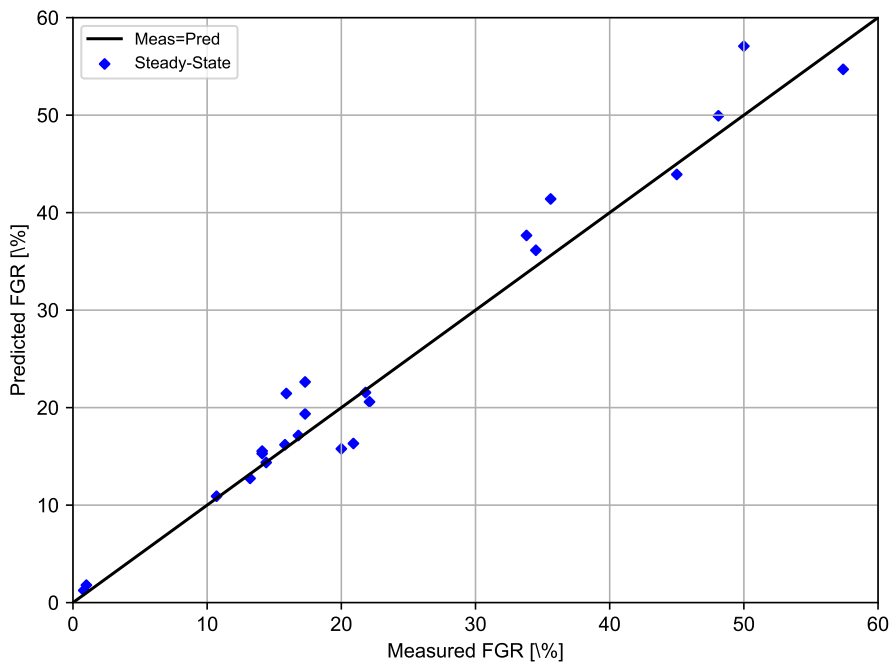
Four fuel rods with  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel were available for assessment of the code's ability to predict FGR in  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel. This is not a large database, but these comparisons seem to indicate that FAST will predict FGR from  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel well. This is consistent with the observation that the measured FGR from  $\text{UO}_2\text{-Gd}_2\text{O}_3$  rods is similar to the FGR from  $\text{UO}_2$  rods with the same power history [Hirai et al., 1995].

The assessment in this section has used the default FGR model in the MASSIH subroutine in the code that is based on a modified release model proposed by [Forsberg and Massih, 1985]. This release model is described in Volume 1 of this report [Porter et al., 2020]. The other FGR models in FAST (i.e., ANS-5.4 and FRAPFGR) provide reasonable predictions of FGR for fuel rods with steady-state power histories, but on average underpredicted FGR for fuel rods with power bumping for a few hours duration.

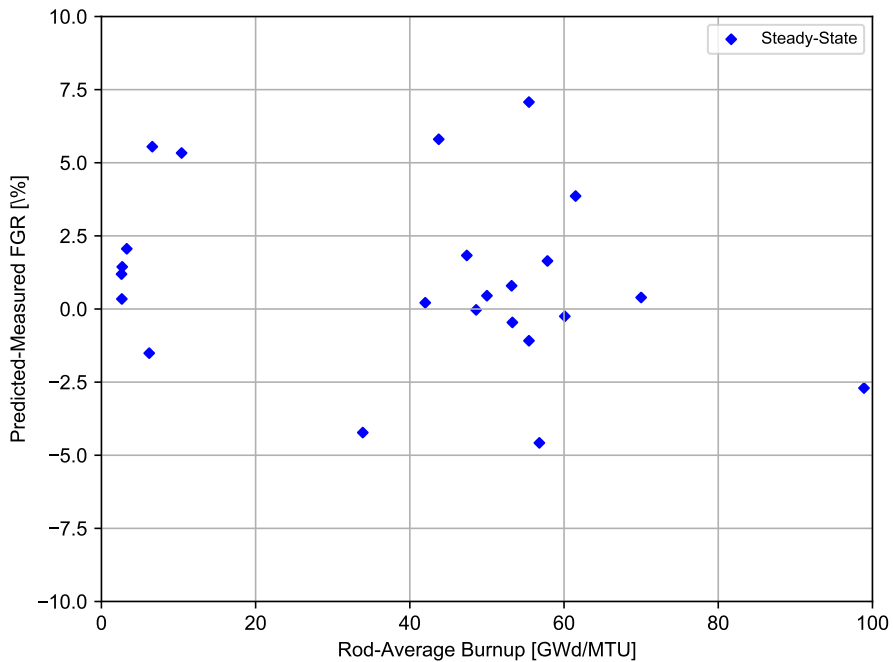
The following discussions are divided into comparisons of the code predictions to steady-state FGR data and to power bumping (transient) FGR data

#### 4.1.1 $\text{UO}_2$ Steady-State FGR Predictions

Figure 4-1 shows the predicted FGR as a function of measured FGR for the steady-state  $\text{UO}_2$  rods. Figure 4-2 shows the predicted minus measured FGR as a function of burnup for the steady-state  $\text{UO}_2$  rods.



**Figure 4-1.** Comparison of FAST predictions to measured FGR data for the UO<sub>2</sub> steady-state assessment cases



**Figure 4-2.** Predicted minus measured FGR versus rod-average burnup for the UO<sub>2</sub> steady-state assessment cases

The steady-state UO<sub>2</sub> cases with measured and predicted FGRs are shown in Table 4-1. The

standard deviation for the steady-state predictions is 2.6% absolute FGR up to 70 [GWd/MTU]. These figures demonstrate that FAST provides a best-estimate calculation of fission gas over a wide range of gas release levels up to a rod-average burnup of 62 [GWd/MTU]. There are a few cases at higher burnup, but these cases indicated that FAST may begin to underpredict FGR at burnup levels beyond 62 [GWd/MTU] (Figure 4-2).

**Table 4-1. Steady-state UO<sub>2</sub> FGR assessment cases**

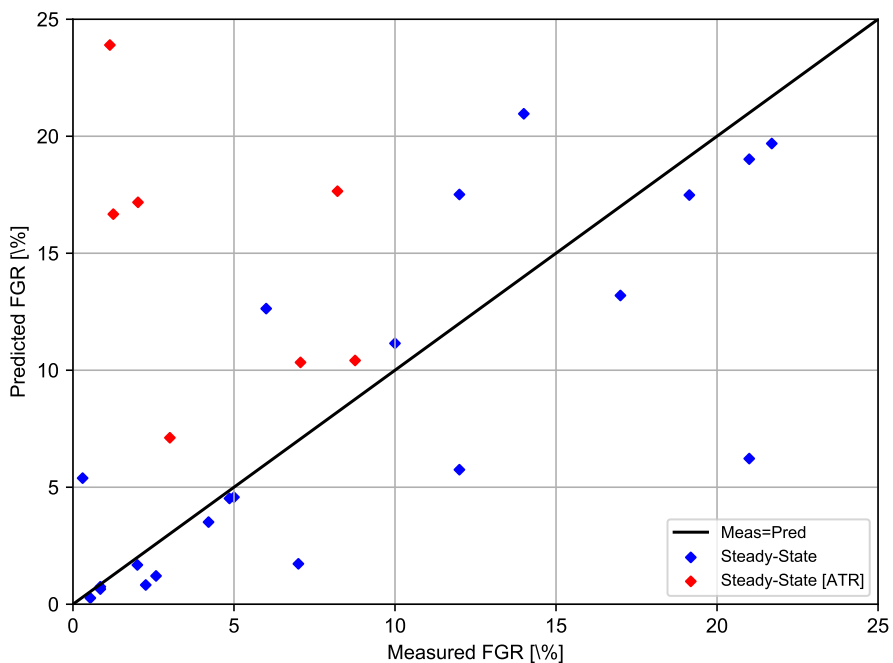
| <b>Rod</b>    | <b>Rod-Average Burnup [GWd/MTU]</b> | <b>Measured FGR [%]</b> | <b>FAST-1.0 Predicted FGR [%]</b> |
|---------------|-------------------------------------|-------------------------|-----------------------------------|
| 24i6          | 60.10                               | 21.80                   | 22.70                             |
| 36i8          | 61.50                               | 33.80                   | 38.09                             |
| 111i5         | 48.60                               | 14.40                   | 14.79                             |
| 28i6          | 53.30                               | 13.20                   | 13.44                             |
| HBEP BNFL-DE  | 42.00                               | 10.70                   | 10.24                             |
| LFF           | 3.29                                | 17.30                   | 19.35                             |
| CBP           | 2.61                                | 14.10                   | 14.51                             |
| 4110-ae2      | 6.20                                | 22.10                   | 16.56                             |
| 4110-be2      | 6.60                                | 15.90                   | 16.65                             |
| 332           | 56.80                               | 20.90                   | 17.24                             |
| EPL-4         | 10.40                               | 17.30                   | 20.72                             |
| CBR           | 2.70                                | 14.10                   | 15.58                             |
| CBY           | 2.65                                | 16.80                   | 16.73                             |
| HBEP BNFL5-DH | 33.90                               | 20.00                   | 15.73                             |
| FUMEX 6f      | 55.45                               | 45.00±5.00              | 42.99                             |
| FUMEX 6s      | 55.45                               | 50.00±5.00              | 56.34                             |
| IFA 597.3     | 70.00                               | 15.80                   | 14.55                             |
| IFA429DH      | 98.90                               | 57.40                   | 54.36                             |
| ANO TSQ002    | 53.20                               | 1.00                    | 1.78                              |
| Oconee 15309  | 50.00                               | 0.80                    | 1.25                              |
| 30i8          | 57.85                               | 34.50                   | 36.78                             |
| m2-2c         | 43.75                               | 35.60                   | 41.25                             |
| pa29-4        | 47.39                               | 48.10                   | 45.80                             |

\* EOL FGR estimated from rod pressure data (larger error than data from puncture)

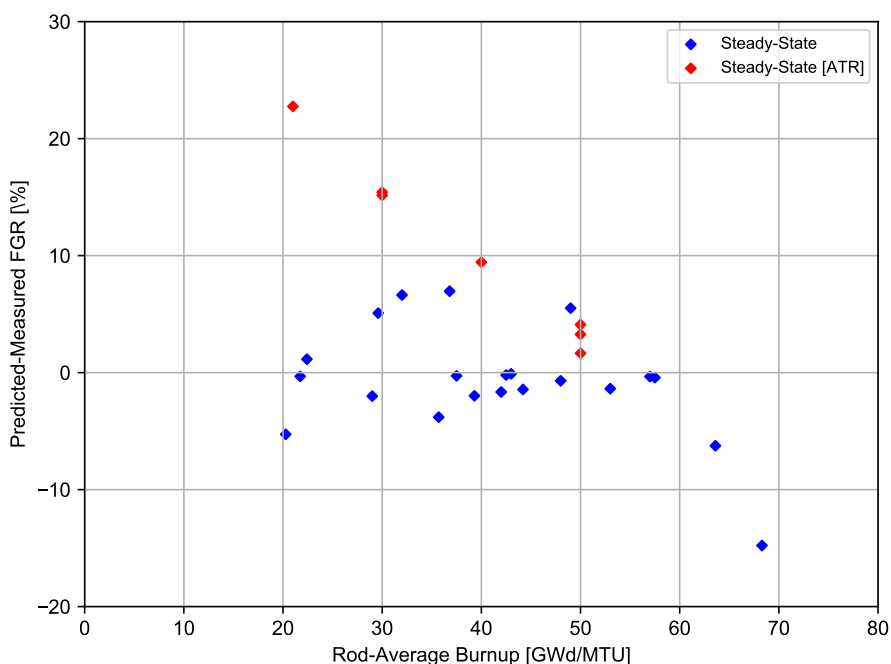


### 4.1.2 MOX Steady-State FGR Predictions

Figure 4-3 shows the predicted FGR as a function of measured FGR for the steady-state MOX rods. Figure 4-4 shows the predicted minus measured FGR as a function of burnup for the steady-state MOX rods.



**Figure 4-3.** Comparison of FAST predictions to measured FGR data for the MOX steady-state assessment cases



**Figure 4-4.** Predicted minus measured FGR versus rod-average burnup for the MOX steady-state assessment cases

The steady-state MOX cases with measured and predicted FGRs are shown in Table 4-2. The standard deviation for the steady-state predictions is 6.8% FGR. It is noted that some of these MOX rods are from the Advanced Test Reactor (ATR) at Idaho National Laboratory and are subject to large radial flux profiles. Because of this, it is difficult to estimate the rod-average power. If the ATR rods are removed from the calculation of standard deviation, a standard deviation of 4.4% absolute FGR is calculated. These figures demonstrate that FAST provides a best-estimate calculation of fission gas over a wide range of gas release levels up to a rod-average burnup of 62 [GWd/MTU]. There are a few cases at higher burnup, but these cases indicated that FAST may begin to underpredict FGR at burnup levels beyond 62 [GWd/MTU] (Figure 4-4).

**Table 4-2.** Steady-state MOX FGR assessment cases

| Rod              | Rod-Average Burnup [GWd/MTU] | Measured FGR [%] | FAST-1.0 Predicted FGR [%] |
|------------------|------------------------------|------------------|----------------------------|
| IFA-651.1r1      | 22.41                        | 10*              | 11.13                      |
| IFA-651.1r3      | 21.73                        | 2*               | 1.68                       |
| IFA-651.1r6      | 20.27                        | 7*               | 1.88                       |
| ATR PII C2 P5    | 21.00                        | 1.146            | 22.19                      |
| ATR PIII C3 P6   | 30.00                        | 1.253            | 15.96                      |
| ATR PIII C10 P13 | 30.00                        | 2.019            | 16.98                      |
| ATR PIV C4 P7    | 40.00                        | 8.214            | 18.69                      |

**Table 4-2. Steady-state MOX FGR assessment cases (continued)**

| <b>Rod</b>            | <b>Rod-Average Burnup<br/>[GWd/MTU]</b> | <b>Measured FGR<br/>[%]</b> | <b>FAST-1.0<br/>Predicted FGR<br/>[%]</b> |
|-----------------------|---|-----------------------------|---|
| ATR PIV C5 P8         | 50.00                                   | 3.009                       | 7.12                                      |
| ATR PIV C6 P9         | 50.00                                   | 7.066                       | 10.11                                     |
| ATR PIV C12 P15       | 50.00                                   | 8.761                       | 9.87                                      |
| Gravelines N06        | 48.00                                   | 4.210                       | 3.50                                      |
| Gravelines N12        | 57.00                                   | 4.860                       | 4.48                                      |
| Gravelines P16        | 53.00                                   | 2.580                       | 1.21                                      |
| IFA-629.1             | 29.00                                   | 21.700                      | 19.13                                     |
| IFA-606 Phase 2       | 49.00                                   | 12.000                      | 17.00                                     |
| IFA 633.1r6           | 32.00                                   | 6.000                       | 12.66                                     |
| M504 H8               | 37.50                                   | 0.540                       | 0.26                                      |
| M504 I2               | 43.00                                   | 0.850                       | 0.75                                      |
| M504 K9               | 42.50                                   | 0.850                       | 0.65                                      |
| M504 M9               | 44.20                                   | 2.260                       | 0.82                                      |
| IFA-597.4/.5/.6/.7r10 | 35.70                                   | 17.000                      | 13.17                                     |
| IFA-597.4/.5/.6/.7r11 | 36.80                                   | 14.000                      | 20.95                                     |
| IFA-629.3r5           | 68.30                                   | 21.000                      | 6.28                                      |
| IFA-629.3r6           | 63.60                                   | 12.000                      | 5.73                                      |
| E09 Rods Inner        | 29.60                                   | 0.200                       | 5.66                                      |
| E09 Rods Inner        | 29.60                                   | 0.400                       | 5.66                                      |
| E09 Rods Intermediate | 39.30                                   | 21.000                      | 19.05                                     |
| E09 Rods Intermediate | 39.30                                   | 21.000                      | 19.05                                     |
| E09 Rods Outer        | 42.00                                   | 19.500                      | 17.86                                     |
| E09 Rods Outer        | 42.00                                   | 18.200                      | 17.86                                     |
| E09 Rods Outer        | 42.00                                   | 19.500                      | 17.86                                     |
| E09 Rods Outer        | 42.00                                   | 18.900                      | 17.86                                     |
| E09 Rods Outer        | 42.00                                   | 19.600                      | 17.86                                     |
| M308 Segment 2        | 57.50                                   | 5.000                       | 4.24                                      |

\* End-of-Life FGR estimated from rod pressure data (larger error than data from puncture)

### 4.1.3 UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> Steady-State FGR Predictions

The four steady-state UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> cases with measured and predicted FGRs are shown in Table 4-3. The standard deviation for these four predictions is 0.3% absolute FGR. Based on this comparison, it appears that the modified Massih model employed by FAST to describe FGR for UO<sub>2</sub> fuels can provide reasonable predictions for FGR from UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> fuel. It is noted that the burnup range is limited (34-40 [GWd/MTU]) and the gas release values are small. Therefore, it cannot be fully confirmed that this conclusion will hold for high burnup. However, this observation is consistent with previous studies conducted by [Delorme et al., 2012] and [Arana et al., 2012]. Delorme studied an irradiated M5<sup>TM</sup>-clad fuel rod containing UO<sub>2</sub> doped with 8 wt% Gd. The rod average burnup was 39.2 [GWd/MTU] and exhibited 0.51% FGR. Although an enhanced high burnup structure was observed and attributed to the chemical effect of Gd additions, the FGR data was consistent with UO<sub>2</sub> rods irradiated to similar levels of burnup, although the measured FGR values are very low. Arana characterized the FGR from fuel rods subjected to high duty conditions in Vadenllos II as part of a High Burnup Program (PAQ). Gd-doped rods containing 2 and 8 wt% Gd were irradiated to ~50 and 55 [MWd/kgU] under high power and high burnup conditions, respectively. The FGR data from these rods were consistent with the FGR data measured from UO<sub>2</sub> pellets under similar power levels.

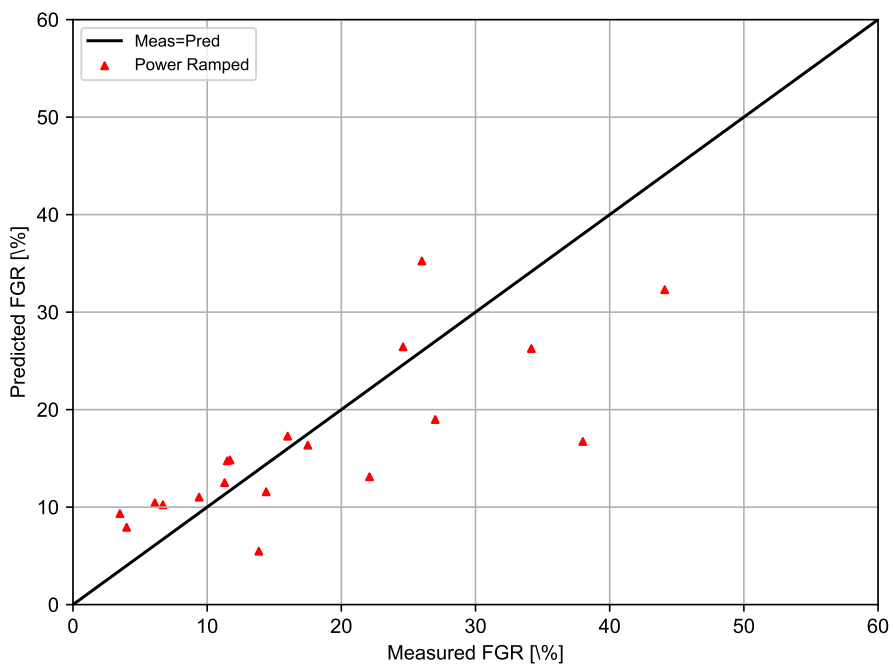
**Table 4-3. Steady-State UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> FGR Assessment Cases**

| Rod      | Rod-Average Burnup [GWd/MTU] | Measured FGR [%] | FAST-1.0 Predicted FGR [%] |
|----------|------------------------------|------------------|----------------------------|
| GAIN 301 | 38.8                         | 0.23             | 0.53                       |
| GAIN 302 | 37.9                         | 0.19             | 0.37                       |
| GAIN 701 | 38.9                         | 0.98             | 0.71                       |
| GAIN 701 | 38.9                         | 0.66             | 0.30                       |

## 4.2 Assessment of Power-Ramped FGR Predictions

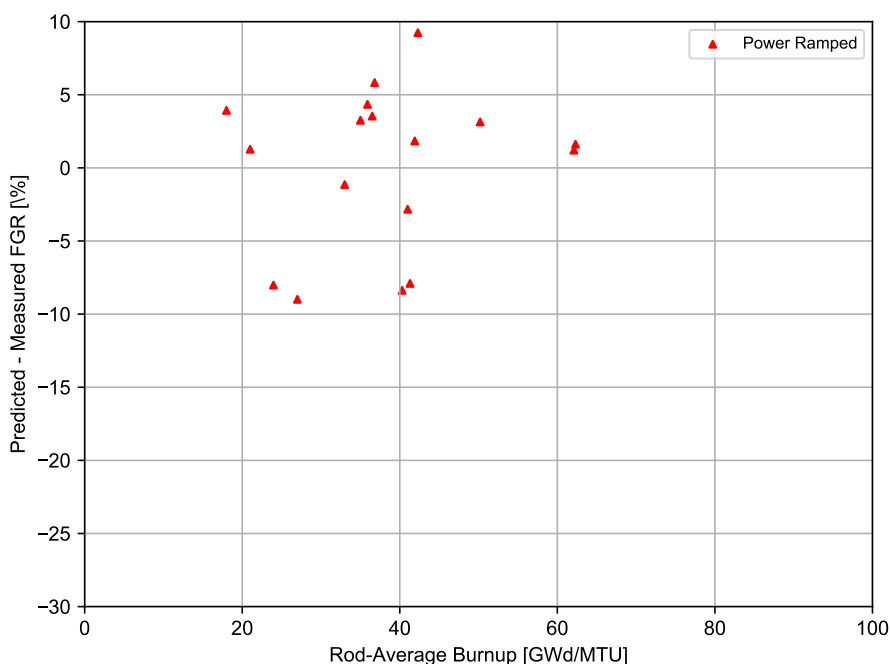
### 4.2.1 UO<sub>2</sub> Power-Ramped FGR Predictions

Figure 4-5 shows the predicted FGR as a function of measured FGR for the power-ramped UO<sub>2</sub> rods.



**Figure 4-5.** Comparison of FAST predictions to measured FGR data for the UO<sub>2</sub> power-ramped assessment cases

Figure 4-6 shows the predicted minus measured FGR as a function of burnup for the power-ramped UO<sub>2</sub> rods.



**Figure 4-6.** Predicted minus measured FGR Versus rod-average burnup for the UO<sub>2</sub> power-ramped assessment cases

The power-ramped UO<sub>2</sub> cases with measured and predicted FGRs are shown in Table 4-4. These comparisons show that the code provides a good prediction of the transient FGR data except for the two High Burnup Effects Program (HBEP) rods, D200 and D226, which are underpredicted by 21% and 12% release, respectively. The fuel in both of these rods is considered atypical of today’s fuel used in commercial rods because it is prone to significant fuel densification (> 2.5% theoretical density (TD)), unlike the less densification prone (stable) fuel (< 1.5% TD) of current fuel designs. In addition, there is evidence that fuel with significant densification releases more fission gas than current stable fuel. The standard deviation for the power-ramped predictions without D200 and D226 is 5.4% absolute FGR. These figures demonstrate that FAST provides a best-estimate calculation of fission gas over a wide range of gas release levels up to a rod-average burnup of 62 [GWd/MTU].

**Table 4-4.** Power-ramped UO<sub>2</sub> FGR assessment cases

| Rod       | Rod-Average Burnup [GWd/MTU] | Measured FGR [%] | FAST-1.0 Predicted FGR [%] |
|-----------|------------------------------|------------------|----------------------------|
| HBEP D200 | 25.00                        | 38.00            | 16.23                      |
| HBEP D226 | 44.00                        | 44.10            | 31.62                      |
| pk6-2     | 36.80                        | 3.50             | 9.19                       |
| pk6-3     | 36.50                        | 6.70             | 10.11                      |
| pk6-S     | 35.90                        | 6.10             | 10.15                      |

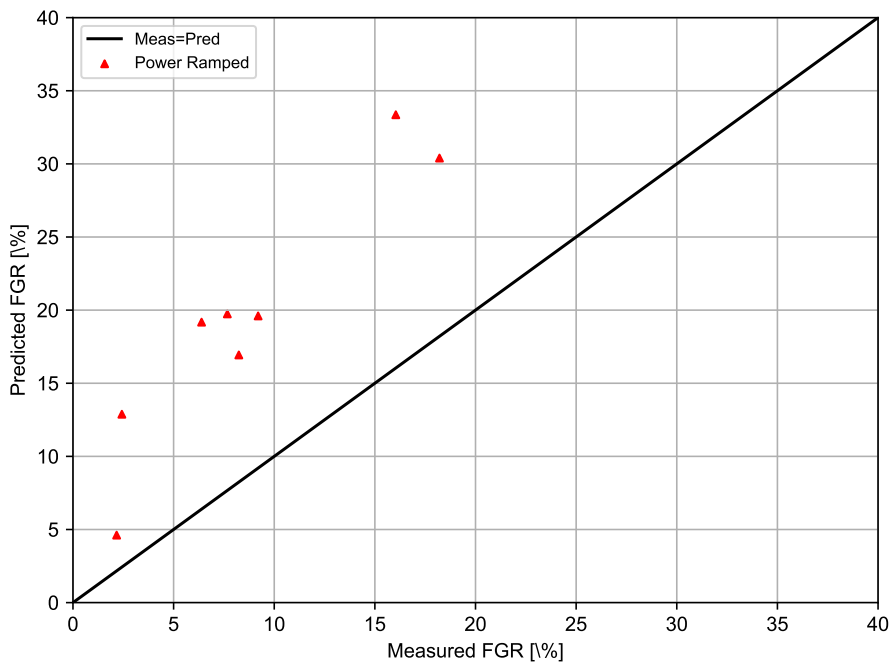
**Table 4-4. Power-ramped UO<sub>2</sub> FGR assessment cases (continued)**

| <b>Rod</b>        | <b>Rod-Average Burnup<br/>[GWd/MTU]</b> | <b>Measured FGR<br/>[%]</b> | <b>FAST-1.0<br/>Predicted FGR<br/>[%]</b> |
|-------------------|---|-----------------------------|---|
| Inter Ramp Rod 16 | 21.00                                   | 16.00                       | 14.84                                     |
| Inter Ramp Rod 18 | 18.00                                   | 4.00                        | 6.48                                      |
| RISØ f14-6.in     | 27.00                                   | 22.10                       | 13.97                                     |
| RISØ f7-3.in      | 35.00                                   | 11.50                       | 13.88                                     |
| RISØ f9-3.in      | 33.00                                   | 17.50                       | 17.24                                     |
| RISØ ge2          | 41.90                                   | 24.60                       | 25.64                                     |
| RISØ ge4          | 23.96                                   | 27.00                       | 18.31                                     |
| RISØ ge6          | 42.29                                   | 26.00                       | 33.64                                     |
| RISØ ge7          | 41.00                                   | 14.40                       | 10.88                                     |
| B&W Studsvik R1   | 62.30                                   | 9.40                        | 11.83                                     |
| B&W Studsvik R3   | 62.10                                   | 11.30                       | 13.16                                     |
| RISØ AN1          | 41.30                                   | 34.16                       | 25.54                                     |
| RISØ AN8          | 40.30                                   | 13.85                       | 5.47                                      |
| regate            | 50.20                                   | 11.70                       | 11.35                                     |

Normal operational transients typically last between 4 and 12 hours, while AOO power transients last less than 30 minutes. Because both of these types of transients can lead to FGR, the NRC requires that both be included in the rod internal pressure analyses to demonstrate that they meet the no cladding liftoff criterion for establishing a rod pressure limit. In general, the short hold time AOO transient results in the lower FGR. However, the burst release typically seen in transients on the order of less than 30 minutes appears to be increasing with increasing burnups, particularly above 62 [GWd/MTU], such that the code may be underpredicting release for short time period transients at high burnup. Therefore, future code verification will examine FGR data with power ramps of short duration.

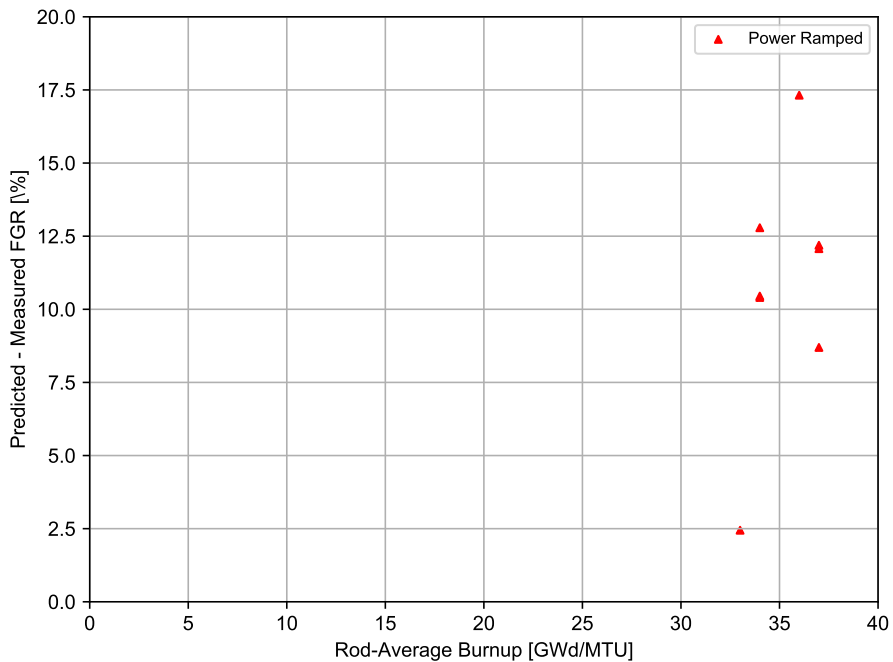
#### 4.2.2 MOX Power-Ramped FGR Predictions

Figure 4-7 shows the predicted FGR as a function of measured FGR for the power-ramped MOX rods.



**Figure 4-7.** Comparison of FAST predictions to measured FGR data for the MOX power-ramped assessment cases

Figure 4-8 shows the predicted minus measured FGR as a function of burnup for the power-ramped MOX rods.



**Figure 4-8.** Predicted minus measured FGR Versus rod-average burnup for the MOX power-ramped assessment cases



The power-ramped MOX cases with measured and predicted FGRs are shown in Table 4-5. The standard deviation for the steady-state predictions is 11.6% absolute FGR and the average deviation (bias) is 10.3% absolute FGR. These figures demonstrate that FAST tends to overpredict the gas release measurement for power-ramped MOX rods. However, it is noted that a limited number of power-ramped rods from only one experimental program are represented here. In addition, it is conservative to overpredict FGR during a power ramp.

**Table 4-5. Power-ramped MOX FGR assessment cases**

| <b>Rod</b> | <b>Rrod-average<br/>burnup<br/>[GWd/MTU]</b> | <b>Measured FGR<br/>[%]</b> | <b>FAST-1.0<br/>Predicted FGR<br/>[%]</b> |
|------------|--|-----------------------------|---|
| M501 HR-1  | 37   | 7.67                        | 19.55                                     |
| M501 HR-2  | 37   | 8.24                        | 16.92                                     |
| M501 HR-3  | 37   | 18.21                       | 29.87                                     |
| M501 HR-4  | 36   | 16.04                       | 31.63                                     |
| M501 MR-1  | 34   | 2.43                        | 12.32                                     |
| M501 MR-2  | 34   | 9.20                        | 19.40                                     |
| M501 MR-3  | 34   | 6.39                        | 18.43                                     |
| M501 MR-4  | 33   | 2.17                        | 5.00                                      |

## 5.0 Internal Rod Void Volume Assessment

### 5.1 Fuel Rod Void Volume

An accurate prediction of the internal void volume of a fuel rod is important in the calculation of the internal rod pressures along with the FGR prediction. The change in the fuel rod void volume with burnup is primarily due to the combined effects of cladding creep, fuel swelling, and axial cladding growth. Nine well characterized fuel rods were selected to assess the capability of FAST to accurately calculate fuel rod void volumes for high burnup. The cases selected include eight full-length rods (rod TSQ002 from ANO-2, rod 15309 from Oconee and rods 2AH3-D15, 2AH3-D12, 0AH5-E14, 07R2D5, AL06-D6, and AD23-D5 from Ringhals 2 and 3) and three short (44 [in] long) rods (36-I-8, 111-I-5, and 24-I-6) that were irradiated in the BR-3 reactor. The Ringhals 3 rods were clad in Optimized ZIRLO™; the Ringhals 2 rods were clad in M5™; the remaining rods were clad with standard Zircaloy-4. All are PWR rods. The burnup levels achieved on these rods range from 33.3 to 62.95 [GWd/MTU]. It would be desirable to include more commercial fuel rods in this assessment, but to date no more fuel rods with reported power histories and measured void volumes have been found.

Table 5-1 presents the measured and FAST-calculated void volume at both BOL and EOL for the eleven fuel rods. The calculations were made at 25 [°C] (77 [°F]) and atmospheric pressure, which should be reasonably close to the temperature at which the data were collected. A range of values for void volume is provided for Oconee rod 15309 because this is the range of void volumes measured from 16 sibling fuel rods from the same assembly—including the representative rod 15309. All 16 rods have very similar EOL burnups and similar power histories. Therefore, the void volume range includes representative uncertainty in the fabricated void volumes, measured rod power histories, and burnup.

**Table 5-1. Measured and calculated void volume for eleven high burnup fuels rods**

| Reactor    | Rod      | Burnup<br>[GWd/MTU] | BOL<br>Measured<br>[in <sup>3</sup> ] | BOL<br>Calculated<br>[in <sup>3</sup> ] | EOL<br>Measured<br>[in <sup>3</sup> ] | EOL<br>Calculated<br>[in <sup>3</sup> ] |
|------------|----------|---------------------|---------------------------------------|---|---------------------------------------|---|
| BR-3       | 36-I-8   | 61.5                | NA                                    | 0.6395                                  | 0.5080                                | 0.656                                   |
| BR-3       | 111-I-5  | 48.6                | NA                                    | 0.6420                                  | 0.5160                                | 0.583                                   |
| BR-3       | 24-I-6   | 60.1                | NA                                    | 0.6401                                  | 0.4910                                | 0.594                                   |
| ANO-2      | TSQ002   | 53.0                | 1.55                                  | 1.5278                                  | 1.0876                                | 1.126                                   |
| Oconee     | 15309    | 49.5 to 49.9        | 2.14                                  | 2.1190                                  | 1.600 -<br>1.700                      | 1.546                                   |
| Ringhals 3 | 2AH3-D15 | 34.1                | NA                                    | 1.2283                                  | 0.9460                                | 0.917                                   |
| Ringhals 3 | 2AH3-D12 | 33.3                | NA                                    | 1.2763                                  | 0.9460                                | 0.943                                   |
| Ringhals 3 | 0AH5-E14 | 57.82               | NA                                    | 1.2826                                  | 0.7930                                | 0.960                                   |
| Ringhals 2 | 07R2D5   | 62.0                | NA                                    | 1.6913                                  | 1.0800                                | 1.240                                   |
| Ringhals 2 | AL06-D6  | 27.97               | NA                                    | 1.4867                                  | 1.2200                                | 1.180                                   |
| Ringhals 2 | AD23-D5  | 62.95               | NA                                    | 1.4440                                  | 1.0800                                | 0.988                                   |

FAST does a good job of calculating the integral fuel rod void volumes, particularly for the commercial reactor rods where as-fabricated void volumes were provided. The three BR-3 test rods are overpredicted by about 20 % on average, but this may be due to an overestimation in the as-fabricated void volumes.

## 6.0 Cladding Corrosion Assessment

Seven well characterized fuel rods were selected to demonstrate the capability of FAST to accurately calculate fuel rod waterside oxidation for high burnup. The cases selected include seven full-length rods (rod TSQ002 from ANO-2; rod 15309 from Oconee; rod A1 from bundle MTB99; rod H8/36-6 from TVO-1; and rods A06, A12, and N05 from Vandellos II). The set includes both PWR and BWR fuel rods that are standard Zircaloy-4, ZIRLO<sup>®</sup>, or M5<sup>™</sup> in PWRs and Zircaloy-2 in BWRs. (These are the cladding alloys currently modeled in FAST.) The rod-average burnup levels achieved on these rods range from 45 to 53 [GWd/MTU]. The corrosion and hydrogen pickup models in FAST have been compared to significantly more separate effects data [Geelhood and Beyer, 2008] [Geelhood and Beyer, 2011] to demonstrate good predictions, but these cases are those with reported power histories and end-of-life measured oxide thickness.

FAST calculated peak oxide layer thicknesses are bracketed by the choice of crud layer thickness for the PWR rods and are in good agreement for the two BWR rods. The purpose of these code-data comparisons is to demonstrate similar predictions as with standalone versions of the corrosion/hydrogen pickup models. The BWR peak corrosion values are fairly well matched by the FAST predictions, and these predictions are not as sensitive to the crud layer input because of the relatively lower heat fluxes and lower operating temperatures.

The conclusion is that the modeling of waterside oxidation is sufficient in FAST for best-estimate analyses. Using integral effect and separate effect data the following standard deviations for each alloy has been calculated or estimated as shown in [Geelhood and Beyer, 2008].

- Zircaloy-2:  $\sigma = 7.6$  [ $\mu\text{m}$ ]
- Zircaloy-4:  $\sigma = 15.3$  [ $\mu\text{m}$ ]
- ZIRLO<sup>®</sup>:  $\sigma = 15$  [ $\mu\text{m}$ ]
- M5<sup>™</sup>:  $\sigma = 5$  [ $\mu\text{m}$ ]

### 6.1 BWR Cladding Corrosion

The only alloy currently used in the United States for BWR conditions is Zircaloy-2. The following assessment shows the FAST predictions of cladding corrosion for two commercial rods with Zircaloy-2.

#### 6.1.1 Zircaloy-2 Corrosion

Table 6-1 shows the measured and FAST calculated peak oxide layer thickness for the two selected high burnup BWR rods.

**Table 6-1.** Peak oxide measured and calculated for two high burnup BWR fuel rods

| Reactor    | Rod          | Burnup [GWd/MTU] | Measured [ $\mu\text{m}$ ] | Calculated [ $\mu\text{m}$ ] |
|------------|--------------|------------------|----------------------------|------------------------------|
| Monticello | MTB99 rod A1 | 45.0             | 25                         | 29                           |
| TVO-1      | H8/36-6      | 51.4             | 28                         | 22                           |

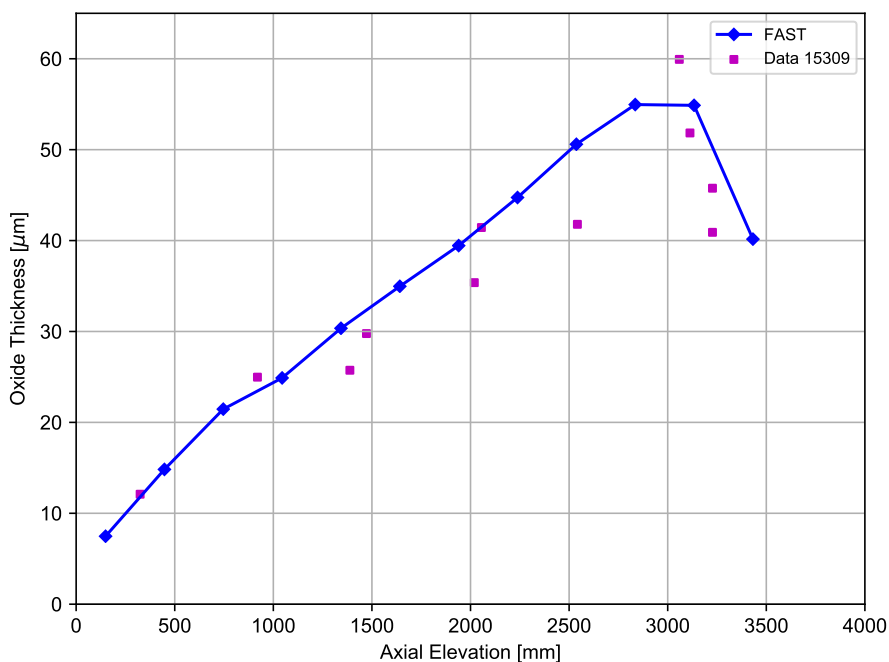
These comparisons indicate satisfactory capability of FAST to predict peak cladding waterside oxidation under BWR conditions.

## 6.2 PWR Cladding Corrosion

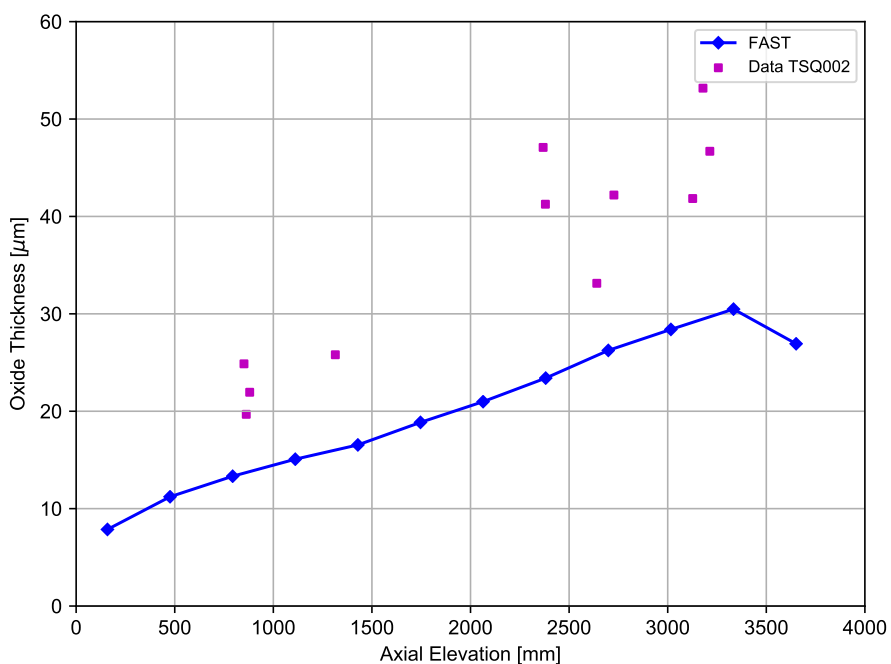
The alloys currently used in the United States for PWR conditions are Zircaloy-4, ZIRLO<sup>®</sup>, Optimized ZIRLO<sup>™</sup> and M5<sup>™</sup>. The following assessment shows the FAST predictions of cladding corrosion for two commercial rods with Zircaloy-4, two commercial rods with ZIRLO<sup>®</sup>, and one commercial rod with M5<sup>™</sup>.

### 6.2.1 Zircaloy-4 Corrosion

Figures 6-1 and 6-2 show the measured and predicted corrosion layer thicknesses as a function of axial position along the rod for the two PWR rods with Zircaloy-4 cladding.



**Figure 6-1.** Measured and predicted corrosion layer thickness as a function of axial position for Oconee 5-cycle PWR Zircaloy-4 Rod 15309, 49.5 [GWd/MTU] (rod-average)

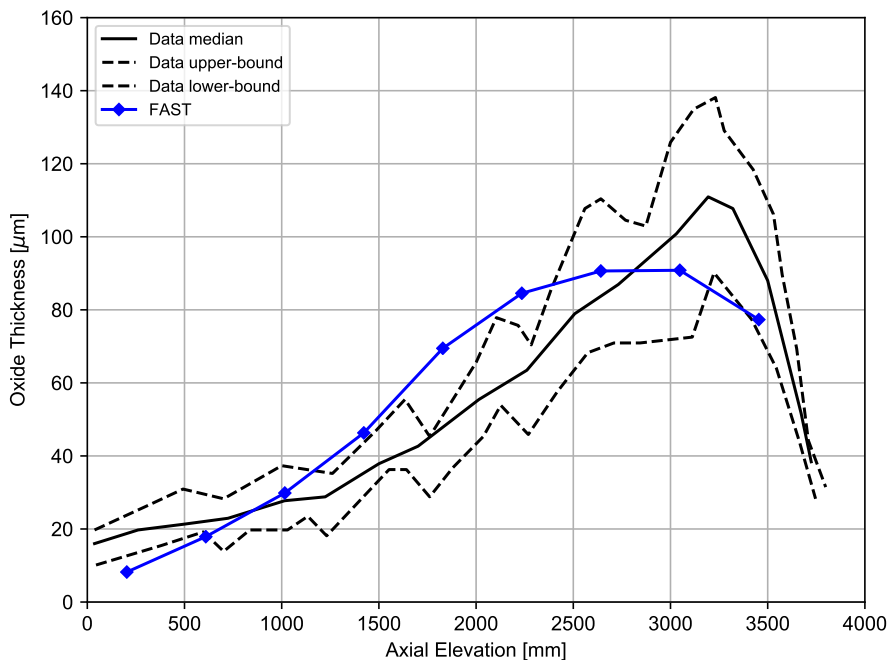


**Figure 6-2.** Measured and predicted corrosion layer thickness as a function of axial position for ANO-2 5-cycle PWR Zircaloy-4 Rod TSQ002, 53 [GWd/MTU] (rod-average)

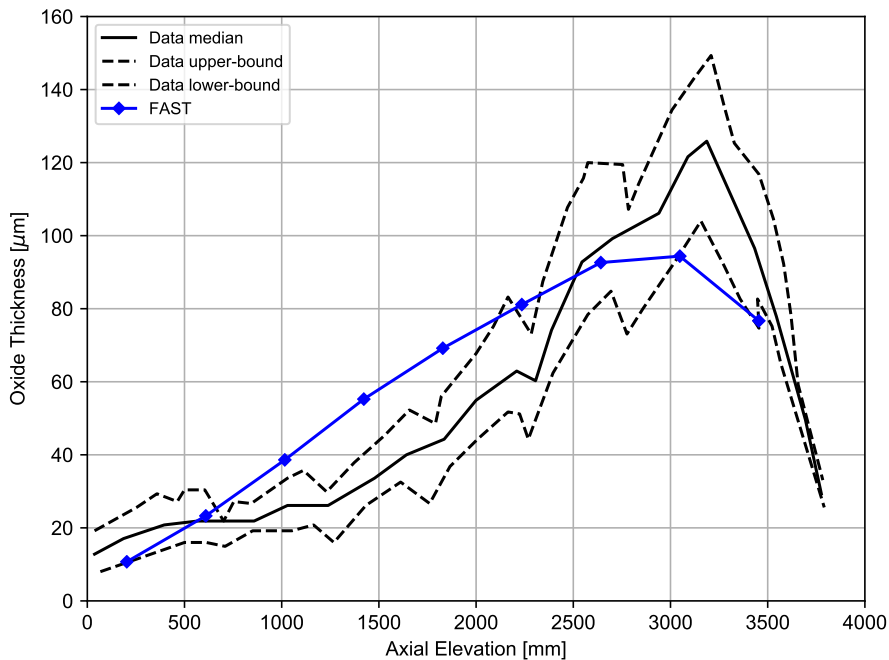
These comparisons indicate satisfactory capability of FAST to predict peak cladding waterside oxidation of Zircaloy-4 under PWR conditions.

### 6.2.2 ZIRLO® Corrosion

Figures 6-3 and 6-4 show the measured and predicted corrosion layer thicknesses as a function of axial position along the rod for the two PWR rods with ZIRLO® cladding.



**Figure 6-3.** Measured and predicted corrosion layer thickness as a function of axial position for Gravelines 5-Cycle PWR ZIRLO® Rod A06, 65.9 [GWd/MTU] (rod-average)



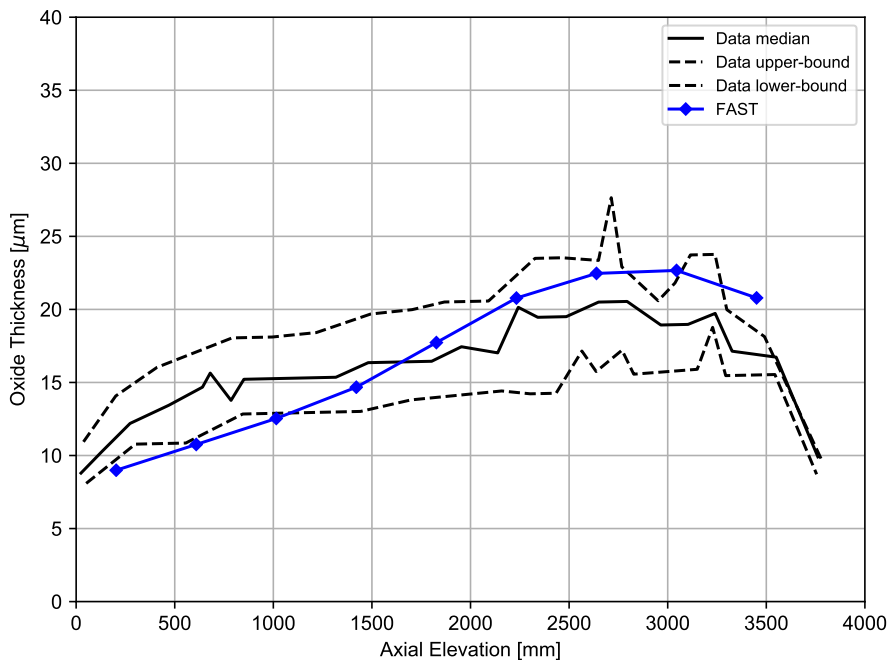
**Figure 6-4.** Measured and predicted corrosion layer thickness as a function of axial position for Gravelines 5-Cycle PWR ZIRLO® Rod A12, 66.4 [GWd/MTU] (rod-average)

These comparisons indicate satisfactory capability of FAST to predict peak cladding waterside

oxidation of ZIRLO® under PWR conditions.

### 6.2.3 M5™ Corrosion

Figure 6-5 shows the measured and predicted corrosion layer thicknesses as a function of axial position along the rod for the PWR rod with M5™ cladding.



**Figure 6-5.** Measured and predicted corrosion layer thickness as a function of axial position for Gravelines 5-Cycle PWR M5™ Rod N05, 68.1 [GWd/MTU] (rod-average)

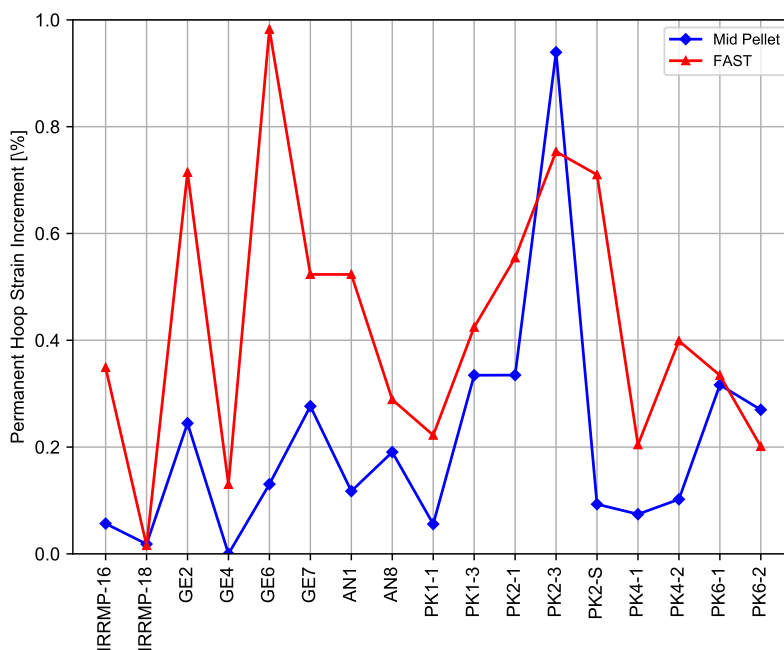
This comparison indicates satisfactory capability of FAST to predict peak cladding waterside oxidation of M5™ under PWR conditions.



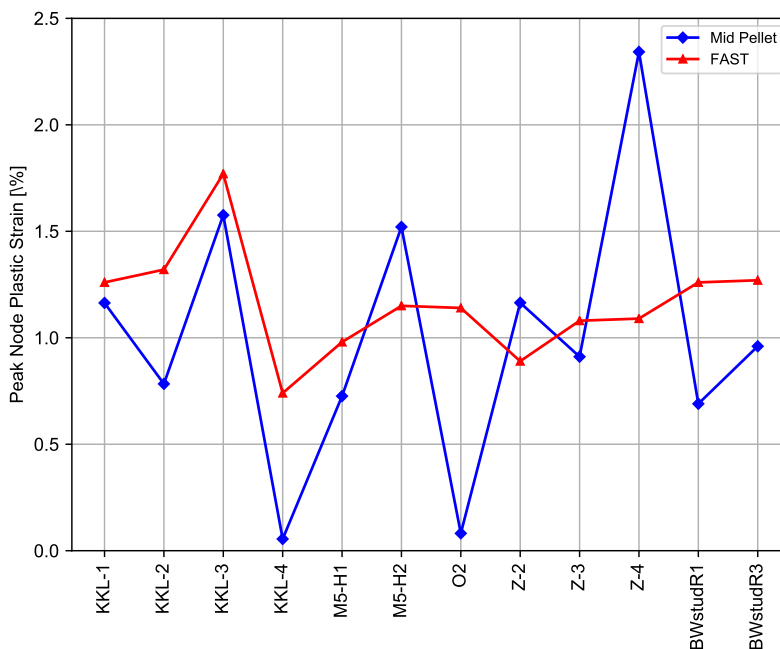
## 7.0 Cladding Hoop Strain During Power Ramps

### 7.1 Assessment Cases

The ability of FAST to predict permanent hoop strain during power ramps was originally assessed against a database consisting of 29 power-ramped rods at burnup levels between 18 and 76 [GWd/MTU] to ramp terminal levels between 30 and 52 [kW/m]. Some of these rods were held at the ramp terminal level for a significant period of time (> 4 [h]) while others were held for a very short period of time (between 1 and 30 [s]). The measured and predicted rod-average permanent hoop strains are shown in Figures 7-1 and 7-2. These figures show that in general FAST overpredicts the measured hoop strain. It was found that FAST overpredicts cladding permanent strain by 0.11% (on average) with significant variation between predicted and measured.



**Figure 7-1.** Measured and predicted rod-average permanent hoop strain for first half of the assessment database

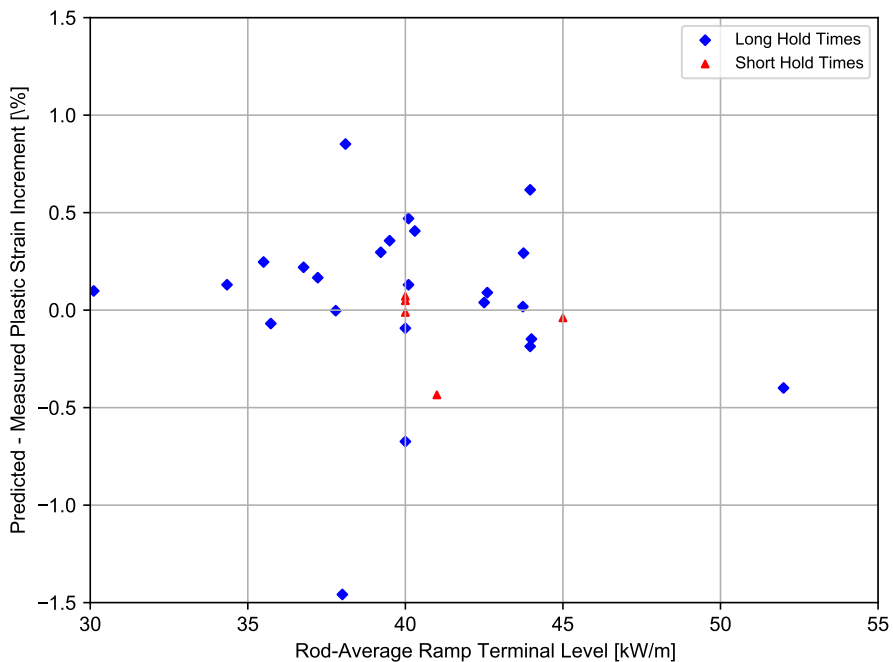


**Figure 7-2.** Measured and predicted peak node permanent hoop strain for second half of the assessment database

This overprediction is consistent with the fact that FAST uses a rigid pellet assumption. This means that the pellet is assumed to be significantly stronger than the cladding such that it will not deform, other than the code-assumed accommodation of 50% of the relocation, when it comes in contact with the cladding.

## 7.2 Comparisons vs. Ramp Terminal Level

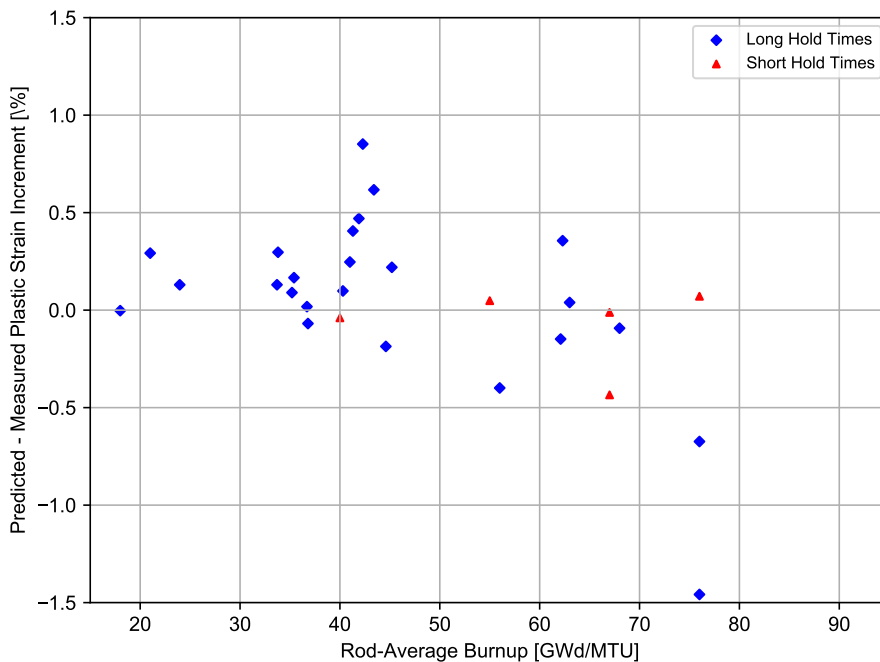
Figure 7-3 shows the predicted minus measured permanent hoop strain for all the assessment cases as a function of ramp terminal power level. There does not appear to be any bias in the predictions with increase ramp terminal power level. However, it does appear that the ramps with short hold times are all overpredicted more than the SCIP ramps with long hold times.



**Figure 7-3.** Predicted minus measured permanent hoop strain as a function of ramp terminal power level

### 7.3 Comparisons vs. Burnup

Figure 7-4 shows the predicted minus measured permanent hoop strain for all the assessment cases as a function of burnup. FAST generally provides a good prediction or slight over-prediction of permanent hoop strain up to 76 [GWd/MTU].



**Figure 7-4.** Predicted minus measured permanent hoop strain as a function of burnup

The FAST predictions for the ramp test data appear to be predicted well up to 62 [GWd/MTU]. There is more scatter in the predictions for power ramps above 62 [GWd/MTU] but other than one ramp test that is significantly underpredicted they also seem to be predicted well.

## 8.0 Conclusions

The FAST steady-state fuel performance code has been assessed against a set of pre-selected data from 137 well characterized fuel rods. The data used for the assessment consisted of measurements of thermal (fuel temperature), FGR, rod internal void volume, and cladding corrosion. The fuel rods represent a range of design parameters, including different fuel rod diameters, lengths, gap sizes, and fill-gas compositions and a wide range of operating conditions with peak LHGRs varying from 8 to 18 [kW/ft], rod-average burnups from 0 to 99 [GWd/MTU], and FGRs ranging from less than 1% to greater than 50%. The estimates of code thermal and FGR predictive error are based on code comparisons to both the benchmark and independent data sets.

- Thermal:** Comparisons were made for BOL UO<sub>2</sub> temperature measurements and UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> temperature measurements as a function of burnup. For the UO<sub>2</sub> BOL temperature measurements, the FAST predictions were within a standard error of 4.6% of measured values and no average bias. For the UO<sub>2</sub> temperature measurements as a function of burnup, the FAST predictions were within a standard error of 4.7% of the measured values. Only IFA-677 rod 2 was underpredicted by up to 150 [K] (11% relative) at BOL. For the MOX temperature measurements as a function of burnup, the FAST predictions were within a standard error of 4.8% of the measured values and much closer in most cases. Only IFA-633.1 was overpredicted by up to 150 [K] (13% relative) at EOL. This overprediction may be due to the code overpredicting the FGR leading to higher fuel temperatures. For the UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> temperature measurements as a function of burnup, the FAST predictions were within a standard error of 4.8% of the measured values and much closer in most cases.

Typically, a standard error of 3 to 4% is the uncertainty in temperature due to power level uncertainty.

Overall, FAST gives reasonable predictions (standard error of less than 5%) of fuel centerline temperature for fuel rods with UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> fuel.

- Fission Gas Release:** Comparisons were made for the UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> FGR measurements for rods with widely varying power levels and burnups. The UO<sub>2</sub> FGR model was assessed for steady-state conditions and power-ramped rods. For the UO<sub>2</sub> cases, a standard deviation of 2.6% FGR (absolute) was calculated for the steady-state rods and a standard deviation of 5.4% FGR (absolute) was calculated for the power-ramped rods when two rods with non-prototypical pellets were removed. These standard deviations are considered reasonable. Although there is little data above 62 [GWd/MTU], it appears that FAST may underpredict UO<sub>2</sub> fuel above this burnup level.

For the MOX cases, a standard deviation of 4.4% FGR (absolute) was calculated for the steady-state rods when the ATR rods with large power uncertainty were removed, and a standard deviation of 11.6% FGR (absolute) was calculated for the limited number of power-ramped rods that all came from one experimental program. The steady-state standard deviation is considered reasonable. The power-ramped rods were all overpredicted, which is conservative for rod internal pressure and temperature calculations. However, a larger database of MOX power-ramped cases is needed to further assess if this overprediction is due to a code deficiency. Although there is little data above 62 [GWd/MTU], it appears that FAST may underpredict MOX fuel above this burnup level.

A limited assessment of UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> data showed good agreement between measurements and predictions using the UO<sub>2</sub> FGR model in FAST. Based on these comparisons and observations by other researchers it was concluded that the FGR from these rods should be conservatively bounded with the UO<sub>2</sub> FGR model.

Overall, FAST gives reasonable predictions (within 5% FGR absolute) of fuel centerline temperature for fuel rods with UO<sub>2</sub>, MOX, and UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> fuel.

- **Internal Void Volume:** Comparisons were made to data from four commercial reactor and three test reactor fuel rods. The code predicted the two commercial rods well but overpredicted the BR3 test rod data by approximately 25% (relative) on average.
- **Cladding Corrosion:** Comparisons were made to data from two commercial BWR rods with Zircaloy-2 cladding, two commercial PWR rods with Zircaloy-4 cladding, two commercial PWR rods with ZIRLO<sup>®</sup> cladding, and one commercial PWR rod with M5<sup>™</sup> cladding. The oxide corrosion predictions were very good and tend to bracket the data. Using integral effect and separate effect data, the following standard deviations for each alloy have been calculated or estimated.
  - Zircaloy-2:  $\sigma = 7.6$  [ $\mu\text{m}$ ]
  - Zircaloy-4:  $\sigma = 15.3$  [ $\mu\text{m}$ ]
  - ZIRLO<sup>®</sup>:  $\sigma = 15$  [ $\mu\text{m}$ ]
  - M5<sup>™</sup>:  $\sigma = 5$  [ $\mu\text{m}$ ]
- **Cladding Hoop Strain:** The original hoop strain assessment cases that were available up to a burnup of around 45 [GWd/MTU] demonstrated that, on average, FAST slightly overpredicts cladding hoop strain by 0.1% strain. FAST overpredicted all the short hold times cases. Despite this overprediction, FAST provides reasonable hoop strain predictions up to 62 [GWd/MTU].

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## Appendix A – Description of Assessment Cases

### A.1 Steady-State Assessment Cases

#### A.1.1 Halden IFA-432 Rods

The IFA-432 test [Lanning, 1986] was irradiated under a research program on fuel rod steady-state performance sponsored by the NRC from 1974 to 1986. The IFA-432 test assembly was a heavily instrumented, six-rod assembly irradiated in the Halden heavy boiling water reactor (HBWR) from 1975 to 1984. The purpose was to test the long-term steady-state performance of BWR-6 type fuel rods, operated at power levels that were at the upper bound for full-length commercial fuel rods. The fuel pellets were fabricated at Pacific Northwest National Laboratory (PNNL) and shipped to Halden; final rod and assembly fabrication was completed at the Halden site. Destructive examinations of selected rods were carried out at Harwell Laboratories, UK.

The assembly included six instrumented rods and three replaceable non-instrumented spares. Each instrumented fuel rod had a centerline thermocouple in both the top and the bottom end of the fuel column and a pressure transducer to monitor rod internal pressure. The assembly instrumentation included six vanadium self-powered neutron detectors (SPNDs) and one cobalt neutron detector, together with rod elongation sensors at each rod position, coolant thermocouples at the top and bottom of the assembly, and a coolant flow meter (turbine).

The test rods were designed to simulate BWR-6 rod cladding type and radial dimensions, with variations in fuel-cladding gap sizes, fuel types, and fill gas compositions. The fuel rod length was much shorter than full-length ( $\sim 144$  [in]) commercial reactor rods to fit well within the short length of the Halden reactor core. Fuel rod overall length was 25 [in], with an active fuel column length of 22.8 [in]. The overall void volume was held to 0.5 [in<sup>3</sup>] (by selection of a  $\sim 1$  [in] plenum length at the upper end); this was done to approximate the ratio between fuel volume and void volume found in full-length rods. The cladding for all rods was Zircaloy-2.

Rods 1, 2, and 3 all had typical high-density (95% TD) stable sintered UO<sub>2</sub> fuel pellets and helium fill gas at 1 [atm] pressure; slight differences in the pellet diameters created variations in fuel-cladding gap size among the rods. Data taken from rod 1 upper and lower thermocouple, rod 2 lower thermocouple, and rod 3 upper and lower thermocouple during the first ramp to power were used in the BOL temperature assessment. Data from the rod 1 lower thermocouple and the rod 3 lower thermocouple were used in the temperature assessment as a function of burnup. It should be noted that much of the helium fill gas was lost from some of these rods during irradiation due to leakage past the thermocouple penetration through the end caps.

#### A.1.2 Halden IFA-513 Rods

The IFA-513 test fuel assembly [Bradley et al., 1981] was irradiated in the Halden reactor from November 1978 to mid-1981 under a continuation of an NRC program to test the performance of BWR-6 type fuel and the effects of fission gas contamination of the helium fill gas.

Rods 1 and 6 both had typical high density (95% TD) stable sintered UO<sub>2</sub> fuel pellets. Rod 1 had helium fill gas at 1 [atm] while rod 6 had 23% xenon and 77% helium fill gas at 1 [atm]. Data taken from rod 1 upper and lower thermocouple and rod 6 upper and lower thermocouple during the first ramp to power were used in the BOL temperature assessment. Data from the rod 1 upper and

lower thermocouple and the rod 6 upper and lower thermocouple were used in the temperature assessment as a function of burnup.

### A.1.3 Halden IFA-633 Rods

The IFA-633 test assembly consisted of six instrumented rods (three short binderless route (SBR) MOX fuel rods and three UO<sub>2</sub> rods) irradiated from BOL through a burnup of 31 [GWd/MTM]. Rod 6 [Wright, 2004] was the only MOX rod instrumented with both a fuel centerline thermocouple and a pressure transducer such that temperature and FGR measurements can be compared. Rods 1, 3, and 5 [Rø and Rossiter, 2005] were UO<sub>2</sub> rods instrumented with centerline thermocouples and were used to assess the FAST predictions of temperature as a function of LHGR at BOL. This test assembly experienced a power ramp at a burnup of approximately 20 [GWd/MTM] to achieve fission gas bubble interlinkage. The MOX fuel was fabricated with the SBR process with a grain size of 7.5 [microns] and was typical of commercial fuel.

Rod 6 was used to assess the FAST temperature predictions for MOX as a function of burnup and the MOX FGR predictions. Rods 1, 3, and 5 were used to assess the FAST temperature predictions for UO<sub>2</sub> as a function of LHGR at BOL.

### A.1.4 Halden IFA-677.1 Rods

The high initial rating test, IFA-677.1 [Thérache, 2005] [Jošek, 2008b], was loaded in the Halden reactor in December 2004 and had completed six cycles of irradiation under HBWR conditions as of September 2007, achieving a rig average burnup of 30 [GWd/MTU]. The single cluster contained six rods supplied by Westinghouse, Framatome ANP, and Global Nuclear Fuel (GNF), all fitted with pressure transducers, fuel centerline thermocouples in both ends, and fuel stack elongation detectors, and with a cladding extensometer for one of the rods. The experiment was aimed at investigating the performance of modern fuels subjected to high initial rating with respect to thermal behavior, dimensional changes (densification and swelling), FGR, and PCMI.

Rod 2 (Framatome ANP), rod 3 (GNF), rod 4 (GNF), and rod 6 (Westinghouse) were all used to assess the BOL UO<sub>2</sub> temperature predictions of FAST as a function of LHGR. In addition, rod 2 was used to assess the UO<sub>2</sub> temperature predictions as a function of burnup up to 32 [GWd/MTU].

### A.1.5 Halden IFA-562 Rod

The Halden Ultra High Burnup (HUHB) test fuel assembly (IFA-562) [Wiesenack, 1992] was initiated by the Halden reactor project to demonstrate the effect of burnup on fuel thermal conductivity. The HUHB configuration of the assembly consisted of six rods, four of which were instrumented with centerline expansion thermometers and two with pressure transducers. The rods were under irradiation in the Halden reactor from September 1989 to 1997. Documented data for fuel center temperatures and linear heat ratings are available to a rod-average burnup of 76 [MWd/MTU].

Four rods (rods 15, 16, 17, and 18) contained “expansion centerline thermometers.” These are tungsten (1.8% ZrO) rods that run the full length of the rod on the inside of the pellets and gauge the average center temperature of each rod via thermal expansion of the rod detected by resistance change. Two rods (rods 13 and 14) each contained a pressure transducer for measuring rod internal pressure. The assembly instrumentation included four SPNDs, three of which were located coplanar at the top of the assembly and one near the bottom to define the thermal neutron flux distribution within the assembly.

The behavior of LHGR and measured temperatures were very similar for all four rods with temperature sensors. One rod (number 18) was selected for comparison to FAST predictions.

### A.1.6 Halden IFA-597.3 Rod

The fuel segments for the high-burnup integral rod behavior test IFA-597 [Matsson and Turnbull, 1998] were refabricated from fuel rod 33-25065, which was irradiated in the Ringhals 1 BWR in Sweden, for approximately 12 years. The irradiation of this rod and its sibling rod 33-25046 was performed in two stages. During the first irradiation, 1980 to 1986, the rods were part of Ringhals assembly 6477 and an approximate rod-average burnup of 35 [GWd/MTU] was reached. The rods were then placed into fuel assembly 9902 for a second period of irradiation from 1986 to 1992 in Ringhals 1. The locations of fuel rods 33-25065 and 33-25046 in this assembly were positions 9902/D5 and 9902/E4, respectively. A final rod-averaged burnup of 59 [GWd/MTU] was achieved. The burnup at the location of the Halden refabricated segments was estimated as 67 [GWd/MTU].

Rods 8 and 9 were loaded into positions 2 and 5 in IFA-597.2 (second loading) and irradiated in Halden for some 20 days in July 1995. After a few power ramps, rod 9 failed and the assembly was withdrawn. During this time, useful data were generated on centerline temperature as a function of power.

Rod 9 was removed and replaced by rod 7. The assembly was returned to the reactor as IFA-597.3 (third loading); the irradiation started in January 1997 and continued to May of that year having accrued a further  $\sim 2$  [GWd/MTU]. Data obtained included centerline temperature as a function of power and burnup, (rod 8), FGR estimated from the increase in rod internal pressure transducer (rod 8), and clad elongation (rod 7).

The assembly was discharged and transported to Kjeller for PIE. FGRs of 12.6% and 15.8% were measured from puncturing and gas extraction from rods 7 and 8, respectively.

Rod 8 was used to assess the  $\text{UO}_2$  temperature and FGR predictions of FAST.

### A.1.7 Halden IFA-515.10 Rods

IFA-515.10 [Tververg and Amaya, 2001] contained hollow rods with centerline thermocouples irradiated up to a burnup of greater than 80 [GWd/MTU]. Two of the rods contain  $\text{UO}_2$  and two of the rods contain 8% gadolinia. However, the gadolinium used in these rods is composed of  $^{160}\text{Gd}$ , which is a non-neutron absorbing isotope. In this way, the effect of the thermal conductivity degradation due to gadolinia can be separated from the power reduction that is typically seen in fuel containing gadolinia. For these rods, a special version of FAST was used that does not use the power profiles for neutron-absorbing gadolinia.

Rods A1 and A2 are sibling rods of  $\text{UO}_2$  and urania-gadolinia ( $\text{UO}_2\text{-Gd}_2\text{O}_3$ ), respectively, and experience very similar power histories. This is also true for rods B1 and B2. Halden has reported that the thermocouples failed in rods A1, A2, and B2 at the burnup indicated on Figures 3-12, 37(b), 38(b).

After this point, the temperature data are no longer valid.

These four rods were used to assess the FAST temperature predictions for  $\text{UO}_2$  and  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel as a function of burnup.

### A.1.8 Halden IFA-681 Rods

IFA-681 [Klecha, 2006] consists of six rods that had been irradiated for four cycles, or 340 days, as of 2006. Ongoing irradiation is currently underway in the Halden reactor. The input files for the  $\text{UO}_2$  rods (rods 1 and 5) have been extended for six cycles to 507 days. All six of these rods were modeled using FAST. Three of these rods contain solid pellets with hollow pellets at the top end and are equipped with centerline thermocouples in the top pellets. These three rods have  $\text{UO}_2$  (rod 1), 2%  $\text{Gd}_2\text{O}_3$  (rod 2), and 8%  $\text{Gd}_2\text{O}_3$  (rod 3) pellets.

The other three rods contain all hollow pellets and are equipped with expansion thermometers. These three rods also have  $\text{UO}_2$  (rod 5), 2%  $\text{Gd}_2\text{O}_3$  (rod 4), and 8%  $\text{Gd}_2\text{O}_3$  (rod 6) pellets, with rod 6 being filled with 50% argon and 50% helium.

For rod 3, there are some overpredictions (50 to 120 [°C]) in the third and fourth cycles. This may be due to error in the temperature measurement or the estimation of the rod power level. This seems likely because the power level during these cycles is reported to increase from about 21 [kW/m] to about 25 [kW/m], while the temperature is reported to remain constant at about 850 [°C]. It also seems strange for the power level in this rod to increase during these cycles while the power level in the other rods is constant during these cycles.

These six rods were used to assess the FAST temperature predictions for  $\text{UO}_2$  and  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel as a function of burnup.

### A.1.9 Halden IFA-558 Rods

IFA-558 [Turnbull and White, 2002] was an assembly commissioned by Central Electricity Generating Board (later Nuclear Electric) to investigate the effect of hydrostatic restraint on the onset of grain boundary interlinkage, and hence, FGR. The assembly comprised six identical, short BWR type rods, each fitted with a pressure transducer and upper and lower fuel centerline thermocouples. The rods contained 7% enriched hollow pellets supplied by British Nuclear Fuels, Ltd. (BNFL) with a 200 [ $\mu\text{m}$ ] cold diametral fuel-to-clad gap. In this way, PCMI effects were minimized, which would otherwise have introduced unwanted uncertainty in the hydrostatic pressure in the fuel pellets.

The assembly was loaded in February 1986 and continued operation successfully until discharge at  $\sim 40$  [GWd/MTU] in March 1992. The fuel rods were subsequently sent to AEA Technology for PIE.

During startup, the rods were filled with helium gas at 2 [bar] pressure. Once the temperatures had stabilized at the prescribed normal operating powers, the pressures of four rods were altered in pairs in such a way as to minimize the spread of temperatures. Subsequently, rods 1 and 2 were operated at the maximum internal pressure of 40 [bar], rods 5 and 6 operated at 20 [bar], while rods 3 and 4 remained at 2 [bar]. These pressures were maintained during all gas flow measurements and were only reduced at cold shutdown for safety reasons. The spread in fuel centerline temperatures during operation at around 35 [kW/m] for rods 2 through 6 was less than 60 [°C], but rod 1 was consistently some 50 [°C] higher.

Radioactive FGR was measured frequently, particularly in rod 3, and the measurements were used to monitor the onset of grain boundary interlinkage. In addition, all gas swept out of the rods was retained in separate cold traps to measure the activity of  $^{85}\text{Kr}$ , which was used to estimate the cumulative release of stable fission gas. This FGR data demonstrated that rod internal pressures

up to 40 [bar] had little effect on FGR.

Rod 6 was used to assess the UO<sub>2</sub> temperature predictions of FAST.

#### A.1.10 Halden IFA-629.1 Rods

The IFA-629.1 [White, 1999] test involved two MOX test rods (rods 1 and 2), but only rod 2 was punctured for FGR measurement such that only this rod will be used for FGR comparison. Both rods are used for the temperature comparison as a function of burnup. The MOX fuel was fabricated using the MIMAS-AUC process by Belgonucleaire (BN). The mother rod for the IFA-629.1 test rods was a full-length PWR MOX rod irradiated for two cycles in the Saint-Laurent PWR, France, with rods 1 and 2 cut as segments from the full-length rod and refabricated into short segments. The rod 2 segment had a burnup of 29 [GWd/MTM] following commercial irradiation, which was extended to 40 [GWd/MTM] during the Halden irradiation. The maximum LHGRs in Halden were significant, at 35 to 40 [kW/m].

These two rods were used to assess the FAST temperature predictions for MOX as a function of burnup. Rod 2 was used to assess the FAST MOX FGR predictions.

#### A.1.11 Halden IFA-610 Rods

One segment from four-cycle PWR MOX EdF rod N016 (which was base-irradiated for four cycles in the French Gravelines-4 reactors to a burnup of approximately 55 [MWd/kgM]) was re-fabricated and instrumented for use in the sequential IFA-610.2,4 cladding liftoff experiments [Beguin, 1999] [Fujii and Claudel, 2001]. The rod was tested under simulated PWR conditions in a pressurized water loop within the Halden reactor. The rod was connected to a gas supply system, and temperature measurements were made in both helium and argon fill gases at varying pressures. Fuel temperature data from helium gas fill periods were used to assess the FAST temperature predictions.

The rod was base-irradiated at nominal LHGRs for  $\sim 1500$  days. The final burnup for the segment was 54.5 [MWd/kgM]. The rod was instrumented with a fuel center thermocouple and a rod elongation sensor. Internal gas pressure was varied throughout the  $\sim 100$  day IFA-610.2 test to investigate the threshold for cladding liftoff. The LHGR level during the IFA-610.2 test was steady at about 14 to 15 [kW/m], and LHGR at the thermocouple was about 13.5 to 14 [kW/m].

In IFA-610.4, the LHGRs were similar at the beginning and drifted downward to 12.5 and 12.0 [kW/m] for rod-average and thermocouple location, respectively [Fujii and Claudel, 2001]. The test duration was similar to that of IFA-610.2 (100 days); however, after 50 days, questions of potential thermocouple degradation were raised, and code data comparison was only conducted over the first 50 days of the test.

These two experiments were used to assess the FAST temperature predictions for MOX as a function of burnup.

#### A.1.12 Halden IFA-648.1 Rods

The IFA-648.1 irradiation [Claudel and Huet, 2001] was simply a burnup extension at low LHGR for two refabricated instrumented segments from Gravelines-4 four-cycle PWR MOX rods, one segment each from rods N12 and P16. The irradiation was carried on at low LHGR under simulated



PWR conditions in a pressurized water loop within the Halden reactor. The rods were then power-ramped in the follow-on IFA-629.3 test to investigate FGR and rod elongation behavior.

The other rods were base-irradiated at nominal LHGRs for  $\sim 1200$  days. The final burnup for the rods N12 and P16 were 57 and 53 [MWd/kgM], respectively. The two rods were instrumented differently upon refabrication. Rod 1 carried a fuel center thermocouple and a rod elongation sensor. Rod 2 carried a fuel center thermocouple and a pressure transducer. The LHGRs were kept deliberately low to accumulate more burnup without inducing FGR.

These two rods were used to assess the FAST temperature predictions for MOX as a function of burnup.

### A.1.13 Halden IFA-629.3 Rods

Following base irradiation in a commercial PWR and further irradiation in Halden, two rods were further irradiated from 62 [GWd/MTU] to 68 to 72 [GWd/MTU]. The MOX fuel was fabricated using the MIMAS (micronized master blend) process. The documentation does not mention whether the  $UO_2$  was fabricated using the ammonium diuranate (ADU) or ammonium uranyl carbonate (AUC) process, but it is likely that the AUC process was used because the fuel was fabricated in the early 1990s. The MOX rods in IFA-629.3 [Petiprez, 2002] were irradiated for four cycles in the Gravelines-4 PWR; after this period, two experimental rods were refabricated from the full-length rods, refilled with helium, and loaded in the IFA 648.1 rig to accumulate more burnup at low powers and no additional gas release. Following irradiation in IFA-648.1, rod 6 was punctured and refilled with helium and the two rods were irradiated in IFA-629.3. These rods were irradiated up to a final burnup of 68 and 72 [GWd/MTM] and discharged for PIE. The measured gas release values for these rods have been obtained by puncture meas

These two rods were used to assess the FAST temperature predictions for MOX as a function of burnup and the MOX FGR predictions.

### A.1.14 Halden IFA-606 Rod

The IFA-606 test assembly [Mertens et al., 1998] [Mertens and Lippens, 2001] consisted of four refabricated rod segments from a full-length PWR MOX rod irradiated in the Beznau-1 reactor, Switzerland, at nominal LHGRs to a burnup of 50 [MWd/kgM]. The MOX fuel was fabricated using the MIMAS-AUC process by BN. Two test rods were instrumented with a fuel thermocouple and a pressure transducer, and irradiated under Halden conditions for approximately 30 days at elevated LHGR in “Phase 2” of the test, to determine FGR behavior. The code-data comparisons presented are for only rod 2 that measured FGR by rod puncture, with a 12.5 micron grain size.

The fuel rod segment was instrumented with a pressure transducer and a fuel centerline thermocouple. The rod was base-irradiated at nominal LHGRs for  $\sim 1500$  days. The rod segment reached a burnup of 49.5 [GWd/MTM] during commercial operation, with additional 30 days of irradiation in Halden for a total burnup of 50.6 [GWd/MTM].

This rod was used to assess the FAST temperature predictions for MOX as a function of burnup and the MOX FGR predictions.

### A.1.15 Halden IFA-636 Rods

IFA-636 [Tverberg et al., 2005] contained both hollow pellets with centerline thermocouples and solid pellets irradiated up to a burnup of 25 [GWd/MTU]. FAST was used to model two of the rods from this assembly. These rods contained 8 % gadolinia of the type typically used in power reactors. Centerline temperature data from IFA-636 rod 2 (hollow pellets) was used to compare to FAST predictions.

Centerline temperature from IFA-636 rod 4 (solid rod) was estimated by Halden based on measurements from IFA-636 rod 2. These estimates were used to compare to FAST predictions. These estimates may have more error than those for rod 2 due to both power uncertainties and uncertainties in estimating rod 4 temperature from rod 2 data.

These two rods were used to assess the FAST temperature predictions for  $\text{UO}_2\text{-Gd}_2\text{O}_3$  fuel as a function of burnup.

### A.1.16 BR-3 Rods

The DOE sponsored high-burnup irradiation of five well-characterized PWR-type test rods [Balfour, 1982] [Balfour et al., 1982] in the BR-3 reactor, located in Mol, Belgium, to demonstrate the feasibility of extending commercial fuel rod burnup and thereby help to minimize radioactive waste disposal. These rods were fabricated by Westinghouse Corporation, whose staff also oversaw the PIEs. The PIE on the rods was carried out in the BR-2 hot cell facility at the Mol site. The rods were of basic PWR radial dimensions. Goal peak burnups exceeded 70 [GWd/MTU].

The test rods were designed to simulate Westinghouse PWR ( $15 \times 15$ ) rod cladding type and radial dimensions, with variations in fuel enrichment and rod position providing variations in power history. The fuel rod length was much shorter than the full-length ( $\sim 144$  [in]) commercial reactor rods and fit well within the short length of the BR-3 reactor core. The fuel rod overall length was 44 [in] with an active fuel column length of 38.4 [in].

Six rods were selected for comparison with FAST FGR predictions: 24-I-6, 36-I-8, 111-I-5, 28-I-6, 30-I-8, and 332. Three of these rods were also selected for comparison with FAST void volume predictions: 24-I-6, 36-I-8, and 111-I-5.

### A.1.17 Zorita Rod

Four fuel assemblies were initially irradiated in Zorita cycles 1 and 2. A total of 41 of the fuel rods in each assembly were removable, and 16 of these rods per assembly had high enrichment (4.08 to 6.6 wt%  $^{235}\text{U}$ ) to achieve high linear power levels and burnups. One of these rods, rod 332 [Balfour et al., 1982], with high enrichment that was irradiated up to 57 [GWd/MTU], was selected as an FGR assessment case for FAST.

### A.1.18 BNFL BR-3 Rods

Battelle, Pacific Northwest Laboratories administered the international group-sponsored High Burnup Effects Program (HBEP), which continued from 1978 to 1990. The objective of the HBEP was to determine the effects of extended burnup on fuel rod performance, especially FGR. A variety of test rods and commercial power reactor rods were irradiated and examined under the HBEP, including two PWR assemblies (366 and 373) [Lanning et al., 1987] [Barner et al., 1990] containing

PWR-type test rods irradiated in a single assembly in the BR-3 test reactor in Mol, Belgium. Both of these assemblies experience high power, and the rods showed significant FGR.

One rod from each assembly (rod DE from 373 and rod 5-DH from 366) was selected to be part of the UO<sub>2</sub> FGR assessment cases for FAST.

#### A.1.19 DR-3 Rods

Test 022 comprised three UO<sub>2</sub>-Zr test fuel pins which were irradiated in the DR-3 reactor at Risø, Denmark, at 7.2 [MPa] (70 [atm]) system pressure [Bagger et al., 1978]. A burnup of approximately 42 [GWd/MTU] was accumulated at heat loads in the range of 35 to 53 [kW/m]. Fission gas analysis for two of the pins (PA29-4 and M2-2C) showed that the releases were 49 and 36% .

The three almost identical test fuel pins had 12.6 [mm] sintered UO<sub>2</sub> pellets of 2.28% enrichment in 128 [mm] long stacks. The cladding was cold-worked and stress-relieved Zircaloy-2 tubing of approximately 0.55 [mm] wall thickness which had been autoclaved on both sides. The diametral pellet-clad clearance was 0.24 [mm], and the pins were backfilled with 0.1 [MPa] (1 [atm]) helium.

These two rods were used to assess the FAST UO<sub>2</sub> FGR predictions.

#### A.1.20 NRX Rods

Several sets of UO<sub>2</sub> fuel rods were irradiated in a pressurized water loop in the NRX reactor in Chalk River, Canada [de Meulemeester et al., 1973] [Notley et al., 1967]. The goal of these tests was to measure the gas pressures inside the rods, with the following objectives:

- To determine the effects of fuel density on gas pressure and FGR.
- To determine the effects of element power output variations on gas pressure and FGR.
- To obtain data to test the predictions of a model for calculating the variation of gas pressure with power output.

After irradiation, the rods were dimensioned and punctured for fission gas analysis. Samples from the rods were also analyzed for chemical burnup. Five of these rods were selected as UO<sub>2</sub> FGR assessment cases for FAST because they provide FGR data at low burnups (<11 [GWd/MTU]) while the other FGR assessment data were at burnups greater than 20 [GWd/MTU]. Rods CBR, CBY, and CBP were irradiated together to 2.7 [GWd/MTU] in 85 days. Rod LFF was irradiated to 3.3 [GWd/MTU] in 108 [days]. Rod EPL-4 was irradiated to 10.4 [GWd/MTU] in 100 days.

#### A.1.21 EL-3 Rods

Sixteen cartridges, each containing two rods, were irradiated in the EL-3 reactor, France, for a varying number of cycles to achieve burnups from 3 to 12 [GWd/MTU]. The aspects of the rods studied in this project were:

- Macroscopic appearances: crack network, material movement, and dimensional changes
- Microscopic appearances: recrystallization, pore redistribution, and new phases

- Migration of fission products: stable gases released by the fuel and distribution of solid fission products

Each cartridge was constructed of Zircaloy-2 and consisted of two separate stages, each containing a stack of UO<sub>2</sub> fuel 123 [mm] high at each end, and in the central joint, space was provided for cobalt flux indicators. Each stage contained a chromel-alumel thermocouple located in the center of the stack. The cartridges were then filled with helium.

After irradiation, the rods were dimensioned and punctured for fission gas analysis. Gamma scans were done as well as a radiochemical analysis. The rods 4110-AE2 and 4110-BE2 [Janvier et al., 1967] were used to assess the UO<sub>2</sub> FGR predictions of FAST.

Both rods 4110-AE2 and 4110-BE2 contained fuel pellets with an as-fabricated density of 10.52 [g/cm<sup>3</sup>]. AE2 ran at a power of 17.6 [kW/ft] while BE2 ran at a power of 17.8 [kW/ft]. Rods 4110-AE2 and 4110-BE2 were maintained throughout life at constant average LHGRs of 17.6 and 17.8 [kW/ft], respectively. Both ran with a flat axial power profile. The input LHGRs were a flat 17.6 and 17.8 [kW/ft], with a few steps to get up to power.

These two rods were used to assess the FAST UO<sub>2</sub> FGR predictions at burnups less than 15 [GWd/MTU].

#### A.1.22 FUMEX 6f and 6s Rods

Two rods were base-irradiated in the Halden HBWR at low power to 55 [GWd/MTU]. Each of these rods was then refabricated to include pressure transducers and run at higher power while the pressure was being monitored. These rods, FUMEX 6s and FUMEX 6f [Chantoin et al., 1997] were included as FAST UO<sub>2</sub> FGR assessment cases.

#### A.1.23 Halden IFA-429 Rod

The IFA-429 test fuel assembly [Turnbull, 2001] was initiated by NRC-Research and designed and fabricated by Idaho National Laboratory (with fuel pellet fabrication by PNNL) to demonstrate the effect of burnup, power level, and fuel grain size on fuel thermal behavior and FGR. The assembly consisted of 18 original short rods, arranged in three clusters of 6 rods each, and 15 noninstrumented spare and replacement rods. Rod DH is a replacement rod that was reinstrumented with a pressure transducer after it had attained about 30 [GWd/MTU] burnup at relatively low LHGR; the rod was then irradiated in IFA-519 at much higher and variable LHGR as part of a load-follow test, and eventually attained a peak burnup of 99 [GWd/MTU]. The FGR for this rod was obtained by puncture during PIE. It should be noted that the puncture data provided much higher release values than were estimated from the pressure transducer measurements because the rod pressures had exceeded the measurement capabilities of the pressure transducer.

#### A.1.24 Arkansas Nuclear One Unit 2 PWR Rod

DOE sponsored a program with ABB Combustion Engineering and Energy Operations, Inc. to improve the use of PWR fuel. The scope of this project was to develop more efficient fuel management concepts and an increase in the burnup of discharged fuel.

Two 16 × 16 lead test assemblies were irradiated in the Arkansas Nuclear One-Unit 2 reactor (ANO-2). This is a PWR that operates at 2815 [MWt]. One of the assemblies, D039, was irradiated for

three cycles and achieved a burnup of 33 [GWd/MTU]. The other assembly, number D040, was irradiated for five cycles and achieved a burnup of 52 [GWd/MTU].

Rod TSQ002 [Smith et al., 1994], irradiated in assembly D040, was of standard CE  $16 \times 16$  design and contained solid  $UO_2$ . Assembly D040 was irradiated from 1979 to 1988 in ANO-2, cycles two through six. It accumulated 52 [GWd/MTU] assembly-average burnup. Rod TSQ002 accumulated an end-of-life (EOL) rod-average burnup of 56.1 [GWd/MTU]. The rod-average LHGR varied from 2.75 to 6.95 [kW/ft], with the higher values near BOL.

This rod was used to assess the FAST  $UO_2$  FGR predictions, the EOL void volume predictions and the Zircaloy-4 corrosion predictions.

#### A.1.25 Oconee PWR Rod

DOE sponsored a long-term, multi-organizational program on the performance of LWR fuel rods during operation to extend burnups. As part of that program, Babcock and Wilcox (B&W)  $15 \times 15$ -type PWR fuel assemblies were irradiated to 3, 4, and 5 cycles in the Oconee PWR, operated by Duke Power Company. One assembly, 1D45, completed five cycles of irradiation in June 1983, having achieved an assembly average burnup of 50 [GWd/MTU] during 1553 effective full-power days.

Several rods from the assembly were nondestructively and destructively examined in the B&W hot cells. This document summarizes the design and operating parameters for one rod, number 15309 [Newman, 1986]. Fuel density and microstructure, rod growth, cladding oxidation/hydriding, and diametral strain data are available for this rod together with FGR measurement via rod puncture and plenum gas analysis. The FGR for this low-powered rod was  $< 1\%$ ; but the cladding oxidation, growth, and diametral strain were significant.

The rods were standard  $15 \times 15$  full-length PWR rods. The rod initially had a rod-average LHGR of 7 to 8 [kW/ft]; however, this decreased to  $\sim 4$  [kW/ft] by EOL. The axial power profile flattened early and remained relatively flat throughout life.

This rod was used to assess the FAST  $UO_2$  FGR predictions, the EOL void volume predictions and the Zircaloy-4 corrosion predictions.

#### A.1.26 Halden IFA-651 Rods

The IFA-651.1 rig [Blair and Wright, 2004] contained six fuel rod segments. Three of these rod segments contained inert matrix fuel and three rod segments contained MOX fuel. The MOX rods (rods 1, 3, and 6) were modeled with FAST. Rod 1 MOX fuel was fabricated using an SBR that results in a relatively homogenous distribution of the  $PuO_2$  compared to MOX fabricated using the MIMAS process. Rods 3 and 6 were fabricated at Paul Scherrer Institute using a two-stage attrition milling process developed by the Korean Atomic Energy Research Institute. Micrographs provided appear to demonstrate that this process provides a homogenous distribution of  $PuO_2$  similar to that observed in the SBR process.

These rods were irradiated for four cycles in the Halden reactor to a rod-average burnup between 20 and 23 [GWd/MTM]. PIE showed that the fuel in rods 1 and 6 had an in-reactor densification of 2%, while the fuel in rod 3 had an in-reactor densification of 1%. These values have been entered into the code as input parameters. The measured gas release values used for model verification

have been estimated from pressure measurements and are subject to greater uncertainty than measurements made by rod puncture.

These three rods were used to assess the FAST temperature predictions for MOX as a function of burnup and the MOX FGR predictions.

#### **A.1.27 Advanced Test Reactor WG-MOX Rods**

Oak Ridge National Laboratory has reported base-irradiation LHGR histories and post-irradiation FGR for seven fuel pins irradiated in the ATR [Morris et al., 2000] [Morris et al., 2001] [Morris et al., 2005] [Hodge et al., 2002] [Hodge et al., 2003]. These pins were irradiated in stainless steel capsules. Several pins were withdrawn for PIE after Phases II, III, and IV, after the pins had accumulated 21, 30, and 40 to 50 [GWd/MTM], respectively. The fuel used in these pins was fabricated using weapons-grade (WG) plutonium with a process similar to MIMAS. Fuel produced from WG plutonium differs from commercial MOX fuel in two ways. First, the WG MOX has greater amounts of <sup>239</sup>Pu, and second, WG MOX contains small amounts of gallium.

The measured gas release values for these rods have been obtained by puncture measurement.

These three rods were used to assess the FAST MOX FGR predictions.

#### **A.1.28 Gravelines-4 PWR Rods**

The Halden Project has reported base-irradiation LHGR histories and post-irradiation (rod puncture) FGR for three full-length PWR MOX rods from Gravelines-4 reactor, France, which were subsequently sectioned to produce test rods for various instrumented tests [Beguin, 1999] [Fujii and Claudel, 2001] [Claudel and Huet, 2001] [Petiprez, 2002]. These commercial rods did not experience LHGRs in excess of 25 [kW/m] or temperatures in excess of 1500 [K], resulting in measured FGR below 5% .

These three full-length commercial rods were used to assess the FAST MOX FGR predictions.

#### **A.1.29 Beznau-1 M504 Rods**

The M504 program [Cook et al., 2003] [Cook et al., 2004] consisted of four MOX rods irradiated in assembly M504 for four cycles in the Beznau-1 PWR reactor. The MOX fuel was fabricated using the SBR process, which results in a relatively homogenous distribution of the PuO<sub>2</sub>. These rods were irradiated up to a burnup between 37 and 43 [GWd/MTM]. The measured gas release values are relatively low and have been obtained from puncture measurements that have less uncertainty than those estimated from pressure measurements.

These four rods were used to assess the FAST MOX FGR predictions.

#### **A.1.30 Beznau-1 M308 Rod**

In the M308 program [Boulanger et al., 2004], segmented MOX rods were irradiated in the Beznau reactor up to peak burnups of 55 to 60 [GWd/MTM]. The MOX fuel was fabricated using the MIMAS–AUC process by BN, which results in larger PuO<sub>2</sub> particle sizes than the SBR process. Sufficient detail on the power history and measured FGR was provided for Segment 2, such that this segment was modeled using FAST. Only the cladding inner and outer diameters were provided

for this segment; however, since these values were identical to the cladding inner and outer diameters for a Westinghouse  $15 \times 15$  fuel rod, it was assumed the rest of the rod dimensions were the same as for a Westinghouse  $15 \times 15$  fuel rod.

This rod was used to assess the FAST MOX FGR predictions

#### A.1.31 Halden IFA-597.4/5/6/7 Rods

IFA-597.4, 5, 6, and 7 [Koike, 2004] contained two MOX rods, containing fuel that was fabricated with the MIMAS-ADU process. Rod 10 contained mostly solid pellets, with a few hollow pellets at the top of the stack to accommodate the fuel centerline thermocouple. Rod 11 contained all hollow pellets. These rods were irradiated for four cycles in the Halden reactor to a burnup between 35 and 37 [GWd/MTM]. The power history at the thermocouple position was provided for both rod 10 and rod 11. To determine the rod-average LHGR, for rod 10, the power history was increased by the ratio of average power to power at the top of the rod, and the ratio of the volume of a solid pellet to the volume of a hollow pellet. For rod 11, the power history was increased by only the ratio of average power to power at the top of the rod. For these pellets, the out-of-pile re-sintering tests of 24 hours at 1700 [°C] showed a density increase of 0.46%. However, based on in-pile free volume and pressure measurements, it was determined that the maximum densification was 0.8% for rod 10 and 1.4% for rod 11. These measured values were used in the FAST input files.

The measured gas release values used for the FAST assessment have been estimated from pressure measurements and are subject to greater uncertainty than measurements made by rod puncture.

These two rods were used to assess the FAST temperature predictions for MOX as a function of burnup and the MOX FGR predictions.

#### A.1.32 FUGEN Rods

The MOX fuel assembly, E09 [Ozawa, 2004], was irradiated for 10 cycles in the Japanese advanced thermal reactor, Fugen. This assembly reached the highest assembly average burnup of 38 [GWd/MTM]. The rods in this assembly were arranged in a circular pattern consisting of three concentric rings. The power history was approximately the same for all rods in a given ring. However, the power histories given for each ring did not provide the rod-average burnup that was measured in the pellets via gamma scanning. This discrepancy is most likely due to uncertainty in the linear heat rates that were provided. To model these cases, the power histories that were supplied were increased by a factor so the burnup calculated using these histories would be equivalent to the measured burnup.

The pellet stack consisted of pellets with varying plutonium concentration in different axial regions. The top and bottom areas contained more plutonium than the central region. Since it is not possible to specify the plutonium concentration at various axial regions along the pellet stack in FAST, two cases were run. In the first case, the plutonium concentration for the middle section was used for the entire rod, and in the second case, the plutonium concentration for the top and bottom sections was used for the entire rod. This allowed the effect of plutonium concentration on FGR to be seen. Plutonium concentration had very little impact on the predicted FGR (< 5% relative).

The measured gas release values for these rods have been obtained by puncture measurement on several rods from each ring.

These three rods were used to assess the FAST MOX FGR predictions.

### A.1.33 Monticello BWR Rod

A DOE program was completed in 1985 in which nine  $8 \times 8$  fuel assemblies in the Monticello BWR were taken to high burnup (up to 45.6 [MWd/MTM] assembly average), and the rods were periodically examined nondestructively and sampled for destructive examinations [Baumgartner, 1984]. Four of the assemblies went for the “full term” from cycle 3 through cycle 9 from May 1974 to September 1982.

All of these rods have fully annealed Zircaloy-2 cladding. One of these rods, rod A1 from assembly MTB99 was used in the Zircaloy-2 corrosion assessment for FAST.

### A.1.34 TVO-1 BWR Rod

Battelle, Pacific Northwest Laboratories administered the international group-sponsored HBEP, which continued from 1978 to 1990. The objectives of the HBEP were to determine the effects of extended burnup on fuel rod performance, especially FGR. A variety of test rods and commercial power reactor rods were irradiated and examined under the HBEP, including nine full-length 5- and 6-cycle rods from the TVO-1 BWR in Finland [Barner et al., 1990]. One of these rods was used to assess the corrosion performance of FAST for Zircaloy-2: rod number H8/36-6 from 5-cycle fuel assembly 6116.

The rod occupied position H8, which was the control blade corner position. The rod-average burnup at EOL was 44.6 [GWd/MTU], with a peak value (confirmed by chemical burnup analysis) of 50.9 [GWd/MTU]. The rod-average LHGR varied between 12 and 24 [kW/m] (3.3 to 7.6 [kW/ft]), but large variations in the peak-to-average LHGR ratio occurred due to control blade movements.

### A.1.35 Vandellos PWR ZIRLO<sup>®</sup> Rods

A joint Spanish and Japanese effort irradiated a large number of full-length fuel rods for five cycles in the Spanish PWR Vandellos 2 (CSN, ENUSA 2002). The rods were clad with ZIRLO<sup>®</sup> and Mitsubishi Developed Alloy (MDA). Two of the ZIRLO<sup>®</sup> rods (A06 and A12) have been modeled with FAST to assess the performance of the ZIRLO<sup>®</sup> corrosion model to high burnup.

### A.1.36 Gravelines-5 PWR M5<sup>™</sup> Rod

One high-burnup rod was taken from the French reactor Gravelines-5 and refabricated for the RIA test CIP0-1, performed in the CABRI reactor, France [Segura and Bernaudat, 2002]. This rod, N05, was clad with M5<sup>™</sup>. Before refabrication, rod N05 was examined and the oxide layer thickness was measured. This full-length commercial rod has been modeled with FAST to assess the performance of the M5<sup>™</sup> corrosion model to high burnup.

### A.1.37 GAIN UO<sub>2</sub>-Gd<sub>2</sub>O<sub>3</sub> Rods

The GAIN Programme, which was an international program lead by Belgonucleaire, irradiated four rods with two different doping concentrations. Rods 301 and 302 were doped with 3wt% Gd while rods 701 and 702 were doped with 7wt% Gd. All four rods were irradiated in BR3 for four cycles, but rod 701 was removed for transient tests between cycles in BR2 [Hoffmann and Kraus, 1984] [Manley et al., 1989] [Reindl et al., 1991]. FGR measurements were obtained from each rod.



## A.2 Power-Ramp Assessment Cases

### A.2.1 Ramped HBEP Obrigheim/Petten Rods

The HBEP was an international, group-sponsored program administrated by Battelle Pacific Northwest Laboratory from 1979 to 1989 [Barner et al., 1990]. The objective was to investigate the impact of extended burnup on fuel rod performance, especially FGR. A total of 81 rods of both BWR and PWR types were irradiated and examined under the program, with rod-average burnups ranging up to 69 [GWd/MTU] and peak pellet burnups up to 83 [GWd/MTU].

Under Task 2 of the program, full-length segmented rods were irradiated in commercial power reactors and then subjected to power ramps in test reactors. The rod segments comprised “rodlets” that were individual short-length fuel rods, mated end-to-end to form the full-length rods. Following irradiation to a variety of burnup levels, the rods were disassembled into the individual rodlets, and the rodlets were ramp-tested in test reactors. The peak LHGRs in these ramps ranged from 35 to 50 [kW/m], and hold times ranged from 48 to 196 hours. The FGR during bumping was a function of the peak LHGRs and ranged from 10 to 45% . The pre-bump LHGRs ranged from 15 to 35 [kW/m], as confirmed by calibrated nondestructive <sup>85</sup>Kr activity determinations for the plenum gas, and the pre-bump FGRs were generally low (1 to 5% ).

Two PWR-type ramped rodlets were chosen for comparison to FAST predictions. Both were fabricated by Kraftwerk Union (KWU), irradiated in the same fuel assembly in the Obrigheim PWR, Germany, and then power-ramped to approximately the same peak LHGR (41 to 43 [kW/m]) in the JRC-Petten test reactor, the Netherlands. Rodlet D200 attained 25 [GWd/MTU] burnup in one reactor cycle at LHGRs of 25(2) [kW/m]. Rodlet D226 attained 45 [GWd/MTU] by further irradiation in the same assembly for two more cycles, with LHGR generally decreasing with time from 25 [kW/m] at BOL to ~17 [kW/m] during the final cycle. The fuel in these rods resulted in high fuel densification < 2.5% TD and high open porosity that is atypical of today’s fuel. Comparisons of the FGR data from these power-ramped rods to other power-ramped data with lower densification and open porosity fuel typical of today’s fuel suggests that these FGR data are higher than observed from today’s fuel. As a result, the FAST code tended to underpredict this data, which is not surprising.

The post-bump FGR is greater for the higher-burnup rodlet D226 than for rodlet D200 (44 vs. 38% ), despite D226 having a smaller as-fabricated fuel cladding gap. The pre-ramp FGRs, based on <sup>85</sup>Kr activity in the plenums, were very similar: 4.2 and 6.6% , respectively. Therefore, the net FGR during ramping is greater for rodlet D226, and this was attributed to burnup effects. This rodlet pair thus provides a test of the burnup effects inherent in FAST.

### A.2.2 Super-Ramp Rods

The Super-Ramp Project was an international, group-sponsored program involving base-irradiation of segmented full-length BWR and PWR rods in various power reactors, followed by ramp-testing of the rod segments in the Studsvik R-2 test reactor in Sweden [Djurle, 1985]. The project’s purpose was to establish the failure threshold for rods of varying types and burnup, and some rod segments did fail during high-power ramp testing. Rod segments that did not fail, however, gave data on FGR and cladding permanent hoop strain during EOL power transients.

Three rod segments were selected as FGR assessment cases and nine rod segments were selected as cladding hoop strain assessment cases. These were all non-failed PWR rod segments, which had been base-irradiated in the Obrigheim PWR for three cycles up to a burnup of 34 to

37 [GWd/MTU]. The segments were then ramp-tested in the Studsvik reactor to ramp terminal levels as high as 43 [kW/m]. The FGRs and residual cladding hoop strain were measured following the ramp test.

The segmented PWR rods were designed in basic conformance with KWU's  $15 \times 15$  PWR fuel design. The general design specifications are given in Table A15.1. The fuel segment length was short, 39 [cm] overall and 31.5 [cm] active fuel length, to match well within the  $\sim 1$  [m] active length of the Studsvik reactor core. The diametral fuel-cladding gap was 145 [microns] (5.7 [mils]). The fuel pellet density is 95% TD, and the standard KWU densification test is only 2.2 hours at 1700 [°C] rather than the 24 hour densification test at 1700 [°C] required by the NRC as a measure of maximum densification. Therefore, the quoted maximum densification for this fuel "none" may be low, and it may be as great as 1% TD—the latter figure is used as FAST input.

### A.2.3 Inter-Ramp Rods

The Studsvik Inter-Ramp Project objective was to investigate the mechanical failure threshold for BWR  $8 \times 8$  type fuel rods. Short rodlets with standard BWR  $8 \times 8$  dimensions and components were fabricated by ABB/Atom specifically for the project and were base-irradiated to  $\sim 20$  [GWd/MTU] at low LHGRs before EOL ramping at rapid rate to high LHGRs to probe for cladding failure. Hold times at the ramp terminal (LHGR) level were 24 hours for non-failed rods. For the non-failed rods, post-ramp FGR was determined by rod puncture.

Two of the non-failed, ramp-tested Inter-Ramp rods, numbers 16 and 18 [Mogard et al., 1979] [Lysell and Birath, 1979], were selected for FGR and cladding permanent hoop strain assessment.

Twenty short 21 [in] rodlets were fabricated for the test, with nominal  $8 \times 8$  BWR fuel rod characteristics, and there were some departures from these characteristics. Rods 16 and 18 were both "nominal rods" with 6 [mil] diametral gaps, 1 [atm] helium fill, and 95% TD solid, dished fuel pellets. The rods were irradiated in approximate BWR coolant conditions in pressurized loops within the Studsvik reactor. Rods 16 and 18 operated for  $\sim 550$  days at LHGRs ranging from 20 to 40 [kW/m] and achieved burnups of 21 and 18 [GWd/MTU], respectively.

Rods 16 and 18 were then preconditioned for 24 hours at 29 and 25 [kW/m], respectively, and then ramped at a rate of  $\sim 70$  [W/m] per second to terminal levels (maximum peak LHGR values) of 48 and 41 [kW/m], respectively, where they were each held for 24 hours, during which the coolant was monitored for added radioactivity (indicating rod failure). Neither rod failed. Therefore, puncture and FGR determinations were feasible, and were performed.

### A.2.4 Ramped Halden/DR-2 Rods

The Risø Fission Gas Release Project was an international, group-sponsored program administered by Risø Laboratories, from 1980 to 1981. The objective was to investigate the impact of extended burnup and EOL power ramping on FGR in BWR-type fuel rods. This was done by performing power-bumping tests in the DR-2 reactor (Denmark) on 9 of the 14 rods irradiated in test fuel assembly IFA-148. This assembly was operated in the Halden reactor, Norway, from 1968 to 1979. The power ramps featured 24-hour hold periods at the peak power level, with the peak power level varied among the tests. These tests were supplemented by nondestructive examinations before and after the bumping irradiations, rod puncturing/gas analysis on all tested rods, and detailed destructive examinations on selected rods.

Three of the bumped rods were selected as FAST FGR assessment cases: rods F7-3, F9-3, and

F14-6 [Knudsen et al., 1983], which had rod-average burnups of 35, 33, and 27 [GWd/MTU], respectively. The analyses of plenum gas  $^{85}\text{Kr}$  activity before and after bumping were performed, and these were calibrated against the post-bump rod puncture results to yield an estimate of the net FGR caused by the power bumping. Thus, these cases provide the opportunity to assess the transient power induced short-term FGR predictions of the FAST FGR model.

The IFA-148 assembly contained a total of 14 short BWR-type test rodlets, with 7 rods each in two clusters (upper and lower clusters). The fuel pellets were 5% enriched sintered uranium, with some variations in density and grain size. These two assessment cases, the nominal grain size and the fuel pellet densities, are equal (13 to 16 [micron] grain size and density of 93.4% TD, with a 0.6% increase upon resinter). The rods were initially filled with 1 [atm] helium fill gas.

### A.2.5 Risø-3 Ramped Rods

The Risø National Laboratory in Denmark has carried out three irradiation programs of slow ramp and hold tests, so called “bump tests,” to investigate FGR and fuel microstructural changes. The third and final project, which took place between 1986 and 1990, bump-tested fuel re-instrumented with both pressure transducers and fuel centerline thermocouples.

The innovative technique used for refabrication involved freezing the fuel rod to hold the fuel fragments in position before cutting and drilling away the center part of the solid pellets to accommodate the new thermocouple.

The fuel used in the project was from IFA-161 irradiated in the Halden BWR to 52 [GWd/MTU], GE BWR fuel irradiated in Quad Cities 1 and Millstone 1 from 23 to 45 [GWd/MTU], and ANF PWR fuel irradiated in Biblis A (Germany) to 43 [GWd/MTU]. All these rods were subsequently ramped in the DR-3 reactor.

Four of the GE BWR rods (GE2, GE4, GE6, and GE7) [Chantoin et al., 1997] and two of the ANF rods (AN1 and AN8) [Chantoin et al., 1997] were selected to assess the FAST predictions of  $\text{UO}_2$  FGR and cladding hoop strain.

### A.2.6 B&W Rods Ramped at Studsvik

Three well-characterized 1.10 [m] long rodlets that had been irradiated to burnups slightly greater than 62 [GWd/MTU] in ANO-1 were ramp tested in the Studsvik R2 experimental reactor [Wesley et al., 1994]. Peak power levels of 39.5, 42.0, and 44.0 [kW/m] and a 12 hour hold time were selected for these tests. No failures were experienced during testing and no incipient cracks were detected in the cladding during the post-ramp examinations. The FGR after the ramp was measured. Two of these rods (rods 1 and 3) were used in the assessment of the FAST  $\text{UO}_2$  FGR predictions.

### A.2.7 Regate Rod

This Regate experiment [Struzik, 2004] deals with the study of FGR and fuel swelling during power transient at medium burnup. The rod was base-irradiated in the Gravelines-5 PWR and then re-irradiated in the test reactor SILOE in Grenoble, France. Since the rod was initially a segmented rod, the refabrication process prior to loading in the test is minor. In particular, the rod was not purged of its fission gases following refabrication.

The segmented rod consisted of  $\text{UO}_2$  fuel with 4.5% enrichment. It was irradiated up to 47 [GWd/MTU]. In the SILOE reactor, the rod was given a conditioning power step of 195 [W/cm] for 48 hours and then was ramped at 10 [W/cm]/min and held at 385 [W/cm] for 90 minutes. This rod is particularly valuable for examining FGR for power ramps of short time duration because the other power ramped  $\text{UO}_2$  rods used for FAST assessment were for hold times of 4) hours or greater.

This rod was used as part of the FAST  $\text{UO}_2$  FGR assessment.

### A.2.8 Beznau-1 M501 Rods

Two MOX rods were irradiated for three cycles in the Beznau-1 PWR up to a rod-average burnup between 34 and 37 [GWd/MTM]. The MOX fuel was fabricated using SBR that results in a relatively homogenous distribution of the  $\text{PuO}_2$ . One of these rods had a high plutonium enrichment (5.54 wt% ) and one had a medium plutonium enrichment (3.72 wt% ). After this, eight rodlets were refabricated from these two rods. Rodlets HR-1 to HR-4 [White et al., 2001] [Cook et al., 2000] [Cook et al., 2003] [Cook et al., 2004] were refabricated from the high-enrichment rod, number 4463, and rodlets MR-1 to MR-4 [White et al., 2001] [Cook et al., 2000] [Cook et al., 2003] [Cook et al., 2004] were refabricated from the medium enrichment rod, number 7612. These rodlets were ramp tested in the Petten high flux reactor. The ramp consisted of a 60 hour hold time at a preconditioning level followed by a ramp to a higher level with a hold of 12 hours for all the rodlets except MR-4, which was only held at the higher level for 20 minutes. It should be noted that the preconditioning and ramp power levels listed in the documents are the peak node powers. These values have been divided by the peak-to-average ratio to determine the rod-average power levels for these ramp tests.

These eight rodlets were used to assess the FAST MOX FGR predictions.

### A.2.9 Studsvik Cladding Integrity Project Ramped Rods

The Studsvik Cladding Integrity Program (SCIP) has subjected 10 test rods to power ramp testing [Kallstrom, 2005]. Each test rod was subjected to a designated type of ramp test, which included staircase, short hold, long hold, and two-step power ramp tests. Each test rod was fabricated from a rodlet sectioned from a previously irradiated father rod.

Four ramp test rods were made by refabricating rodlets from BWR father rods that had been irradiated in Kernkraftwerk, Leibstadt. These test rods were labeled KKL-1, KKL-2, KKL-3, and KKL-4 and were irradiated to approximately 63, 67, 56, and 40 [MWd/mtU] average rodlet burnup, respectively. Before ramp testing, each rod was conditioned for a designated period of time and LHGR. The first ramp test, KKL-1, was aimed at defining the ramp terminal level where rod failure would occur. The rod was subjected to a staircase ramp, and after six steps of 5 [kW/m] with a 1 hour hold time between steps, the rodlet failed after 40 minutes at an LHGR of 42 [kW/m]. To determine if the failure, which was caused by an outside-in crack, was dependent on burnup, a similar test was performed on KKL-3. A staircase ramp consisting of eight steps at 5 [kW/m] with a 1 hour hold time between steps was performed up to 52 [kW/m]. After holding for 12 hours at 52 [kW/m], no failure was observed in KKL-3. Ramp tests of the other two rods, KKL-2 and KKL-4, were aimed at studying the geometric changes during a power transient and their dependence on burnup. The rods, KKL-2 and KKL-4, were held at 41 and 45 [kW/m] for 30 and 5 seconds, respectively. Neither KKL-2 or KKL-4 failed during ramp testing.

Two ramp test rods, M5-H1 and M5-H2, were fabricated from the same father rod, which had been irradiated in Ringhals 4 PWR and used to study the influence of holding time on geometric

changes. The rods, M5-H1 and M5-H2, had been irradiated to a rodlet-average burnup of 67 and 68 [MWd/kgU], respectively, and conditioned for a designated period of time and LHGR prior to ramp testing. During the short hold and long hold ramp tests, holding times of 5 seconds and 12 hours were used on M5-H1 and M5-H2, respectively, at an LHGR of 40 [kW/m]. Neither rod failed during the ramp test.

Ramp testing was performed on rod O2 (55 [MWd/kgU] burnup) to study geometric changes and PCI. Rod O2 had been previously irradiated in the BWR Oskarshamn 2 to an average rodlet burnup of 55 [MWd/kgU]. A short hold ramp test was performed by holding rod O2 at an LHGR of 45 [kW/m] for 30 seconds. Rod O2 did not fail during the ramp test.

Ramp test rods Z-2, Z-3, and Z-4 had each been irradiated to 76 [MWd/kgU]. Rods Z-3 and Z-4 were irradiated in the PWR North Anna while rod Z-2 was irradiated in the PWR Vandelllos. Rod Z-3 was intended to study the hydrogen embrittlement by ramping the rod to an LHGR of 40 [kW/m] for a 5 second hold. However, failure occurred at an LHGR of 39 [kW/M], which prevented the short hold ramp test from being completed. Rods Z-2 and Z-4 were intended to study delayed hydrogen cracking (DHC), and were subjected to two-step power ramp tests. Rod Z-2 was initially ramped to an LHGR of 35 [kW/m] and held for 6 hours before being ramped to an LHGR of 40 [kW/m] and held for an additional 6 hours. Rod Z-4 was initially ramped to 33 [kW/m] and held for 6 hours before being ramped to 38 [kW/m] and held for an additional 6 hours. The rods, Z-2 and Z-4, did not fail during the two-step power ramp.

These 10 rods were used to assess the FAST predictions of cladding hoop strain.

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