Sister Rod Destructive Examinations (FY23)

Appendix F3: Uncertainty and Conservative Bias in the Cyclic Integrated Reversible-Bending Fatigue Test

Spent Fuel and Waste Disposition

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Paul Cantonwine
Oak Ridge National Laboratory

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SUMMARY

This report documents work performed under the Spent Fuel and Waste Disposition's Spent Fuel and Waste Science and Technology program for the US Department of Energy Office of Nuclear Energy. This work was performed to fulfill, in part, the Level 3 Milestone M3SF-OR010201026 "FY23 M3 draft report on results from testing in FY23," which is a precursor to the Level 2 Milestone M2SF-23OR010201027, "Final Report FY23 ORNL testing on Sibling Pins," within work package SF-23OR01020102.

The calibration of the hot cell Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) was confirmed by comparison to the calibrated out-of-cell CIRFT system because the load cells and linear variable differential transducers (LVDTs) in the hot cell cannot be directly calibrated [F3-1]. A key part of the calibration process was to use the uncertainty in the LVDT-based strain amplitude in the out-of-cell CIRFT as the acceptance criterion for the hot cell CIRFT. The uncertainty in the strain amplitude was defined as two times the standard deviation of the LVDT-based strain amplitude relative to the measured strain amplitude from a strain gage. The uncertainty in the strain amplitude was determined to be ± 0.022% [F3-1].

In addition, during the calibration of the hot cell CIRFT, it was determined that the dynamic correction factor used in processing the data is 1.0 [F3-1] rather than the value used previously (i.e., ~0.82) [F3-2]. This suggests that there is a small conservative bias in the previously reported strain amplitudes for high-burnup fuel rods. However, because this bias results in a conservative change in the reported strain amplitude that is within the uncertainty, the previous dynamic correction factor (~0.82) remains acceptable for strain amplitude calculations when fatigue testing irradiated fuel rods in the hot cell CIRFT.

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REVISION HISTORY

Date	Changes
9/1/2023	Initial release

ABBREVIATIONS AND ACRONYMS

CIRFT	Cyclic Integrated Reversible-Bending Fatigue Tester
LVDT	linear variable differential transformer
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory

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F3-1. INTRODUCTION

The development and application of the Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) has been documented over the past 10 years [F3-3]–[F3-6]. The CIRFT system was developed in collaboration with the U.S. Nuclear Regulatory Commission (NRC) to address the concern that high-burnup fuel rod fatigue performance was degraded compared to cladding-only behavior [F3-4]. Fatigue data measured by CIRFT on high-burnup fuel rods were then used by the NRC to develop a fatigue response curve for pressurized water reactor fuel rods with Zircaloy-4 cladding in NUREG-2224 [F3-7]. Subsequently, CIRFT has been used in the sister rod project to test whether reoriented hydrides associated with vacuum drying influenced the fatigue lifetime, to extend the fatigue testing database to include fuel rods with ZIRLO cladding, and to add to the experience on both Zircaloy-4 and M5 cladding [F3-2]. These data will be used as a reference for subsequent characterization of fuel rods removed from the high-burnup demonstration cask [F3-8] to better understand the effects of long-term dry storage, which can be thought of as a multiyear elevated temperature anneal.

The objective of fatigue testing is to provide data that can be used to develop a best-estimate fatigue curve and a conservative fatigue design curve that accounts for uncertainty and can be compared with actual transportation conditions. The process for defining a design fatigue curve for commercial used fuel rods was developed by Oak Ridge National Laboratory (ORNL) in FY22 [F3-9]. One issue noted in the fatigue evaluation was that the calculated combined uncertainty in the strain amplitude values determined from the measured data was large [F3-9], [F3-10]. It was proposed then to directly measure the uncertainty in the strain amplitude to either validate the calculated combined uncertainty or update the uncertainty based on the measurement data [F3-9]. Thus, the purpose of this appendix is to document the measured uncertainty in the strain amplitude data. In the process, it was determined that there has been a conservative bias in the calculated strain amplitude that is small enough to be within the measurement uncertainty. This observation is discussed herein, and a case is made to continue to include the conservative bias in the data.

F3-2. BACKGROUND

F3-2.1. Calculation of Strain Amplitude in CIRFT

The process of calculating the strain amplitude from the LVDT data is documented in Section F-3.1 of Cantonwine et al.'s FY22 examinations [F3-2]. The strain reported is calculated as

$$\varepsilon = \kappa \times y_{max}, \qquad \text{(F3-1)}$$

where κ is the curvature of the sample when subjected to bending based on LVDT measurements, and y_{max} is the radius of the fuel rod. Thus, this calculated strain is the cladding surface strain when subjected to bending. The calculated uncertainty of the strain amplitude from Montgomery FY21 examinations [F3-10] accounted for the uncertainties in the LVDT measurements and calculation of curvature.

F3-2.2 Calibration of the Hot Cell CIRFT

A calibration confirmation of the CIRFT system in the hot cell was performed to prepare for fatigue testing after a long dormancy [F3-1]. This is referred to as a *calibration confirmation* because the load cells and LVDTs in the hot cell system cannot be directly calibrated like the out-of-cell system. The approach taken to confirm the calibration of the hot cell CIRFT was to perform a suite of tests on three known samples—specifically, three Zircaloy-4 cladding tubes—on an out-of-cell CIRFT system that had been calibrated and then to perform the same suite of tests on two of the known samples in the hot cell CIRFT; the third sample was not inserted into the hot cell because it had a strain gauge attached, which could not be used in the hot cell.. Calibration curves and acceptance criteria were created based on the out-of-cell testing, and the hot cell CIRFT was deemed to be calibrated for the conditions under which the acceptance criteria were met.

The uncertainty and bias in the CIRFT system discussed herein is based on the data collected in the calibration confirmation of the hot cell CIRFT.

F3-3. UNCERTAINTY EVALUATION

As mentioned in Section F3-2.2, three known samples were tested in the calibrated out-of-cell CIRFT system. These are described in Table F3-1.

Table F3-1. Calibration Sample Description [F3-1].

Sample ID	Descriptions
Zr4-W-2	6” long sample mounted in standard end caps; a strain gage is applied to the side opposite to the LVDTs and was originally used to determine the dynamic correct factors for the LVDTs
Zr4-W-5	6” long sample mounted in standard end caps
Zr4-W-6	4” long sample mounted in end caps designed specifically for this length of sample. In this sample, only 1” of the tube is inserted in each end cap

Sample Zr4-W-2 was selected to enable a direct comparison between the strain amplitude calculated from the LVDTs and the strain amplitude directly measured by a strain gauge. In this evaluation, the strain measured by the strain gauge is considered the actual strain known to a high certainty. The high certainty in the strain gauge measurement is reflected in the lack of variability in the strain measurement when repeating the test conditions [F3-1]; that is, the standard deviation of the strain gage data is very small. The measured uncertainty in the LVDT strain amplitude is the variability of the LVDT calculations around the measured strain gauge data, which can be quantified as twice the standard deviation of the LVDT data relative to the strain gauge data. Typically, three independent tests were performed at each test condition to provide a measure of the test-to-test variation.

However, sample-to-sample variation is another source of uncertainty. Thus, samples Zr4-W-5 and Zr4-W-6 were chosen to provide a measure of sample-to-sample variation in the LVDT strain amplitudes; no significant differences caused by the different sample lengths were observed. Therefore, the standard deviation of the LVDT strain amplitudes for the three different samples, each with three independent tests at each test condition, quantifies the uncertainty as a function of the test condition.

The uncertainty in the LVDT strain amplitude is determined by the following method.

Step 1: In the out-of-cell CIRFT system, test Zr4-W-2 over a range of strain amplitudes (0.03% to 0.45%); perform three independent tests at each test condition [F3-1].

Step 2: Plot and correlate the measured strain amplitude from the strain gauge as a function of the measured moment. The correlation for testing at 5 Hz was determined to be as follows [F3-1]:

$$\text{Strain Amplitude (\%)} = 0.0346\text{*Applied Moment (N-m)}-0.0098. \quad \text{(F3-2)}$$

Step 3: In the out-of-cell CIRFT system, test Zr4-W-5 and Zr4-W-6 over a range of strain amplitudes (0.03% to 0.45%) [F3-1].

Step 4: Calculate the LVDT strain amplitudes using the standard process that includes both a correction for Δh and the applicable dynamic correction factor [F3-2].

Step 5: Calculate the standard deviation of the LVDT strain amplitudes relative to the correlation based on the strain gauge measurements. The standard deviation of the LVDT strain amplitudes was calculated to be 0.011% and found to be independent of applied moment [F3-1].

Thus, the uncertainty in the LVDT strain amplitudes (defined herein as 2σ) is ± 0.022%.

This uncertainty defined the acceptance criterion for the hot cell calibration, and the calibration data from the out-of-cell CIRFT are plotted for the 5 Hz test conditions in Figure F3-1. It should be noted that the strain amplitudes of interest in the sister rod testing are below 0.1%.

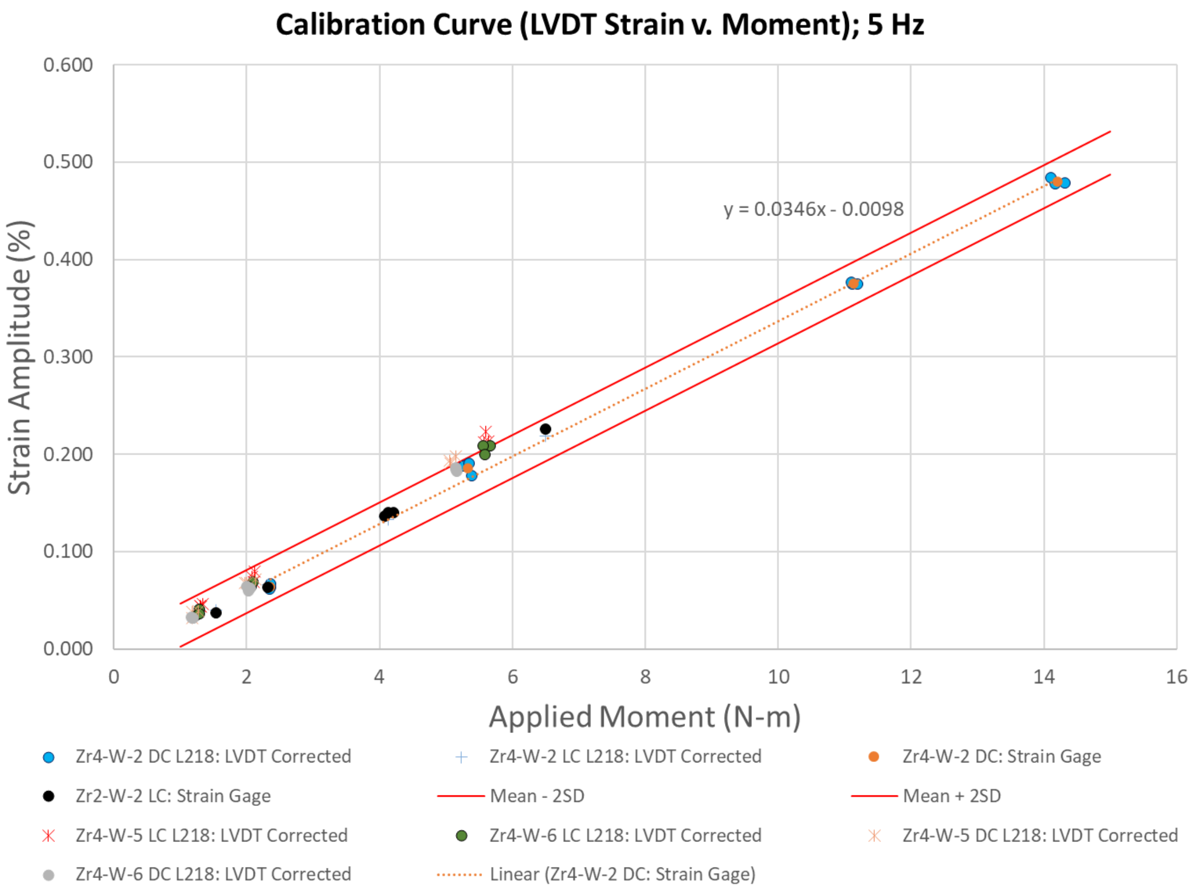

Figure F3-1. Calibration curve for strain amplitude vs. moment based on both displacement-controlled and load-controlled out-of-cell CIRFT testing of Zr4-W-2, Zr4-W-5, and Zr4-W-6 at 5 Hz; LVDT Corrected is the strain amplitude from that LVDT measurements including the standard corrections (Figure 4 from Cantonwine and Wang [F3-1]).

F3-4. CONSERVATIVE BIAS IN THE HOT CELL CIRFT DATA

During the calibration of the hot cell CIRFT, it was observed that the application of the dynamic correction factor from [F3-2] caused a conservative bias in the expected strain amplitude based on the out-of-cell testing. The bias caused the data to be outside the acceptance criterion (i.e., outside the uncertainty) at strain amplitudes greater than ~0.1% (see Figure F3-2). Because the load cell was confirmed to be calibrated at 0.05 Hz, the conclusion was that the load cell remained calibrated at 5 Hz, suggesting that the dynamic correction factor from the out-of-cell CIRFT did not apply to the hot cell CIRFT [F3-1]. Thus, the dynamic correction factor was updated to 1.0 for the hot cell CIRFT. The updated results for both displacement-controlled testing (see Figure F3-3) and load-controlled testing (see Figure F3-4) indicate that the hot cell CIRFT is calibrated with a dynamic correction factor of 1.0.

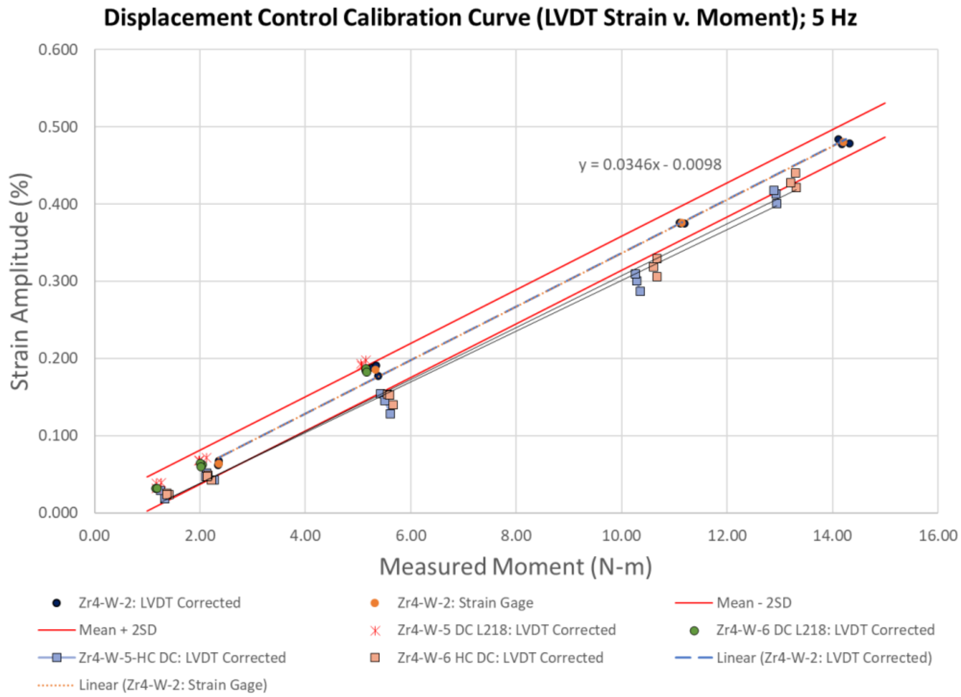

Figure F3-2. The calibration curve provided in Figure F3-1 compared to the hot cell displacement-controlled CIRFT data at 5 Hz using the dynamic correction factor developed for the out-of-cell CIRFT system; LVDT Corrected is the strain amplitude from that LVDT measurements including the standard corrections [F3-1].

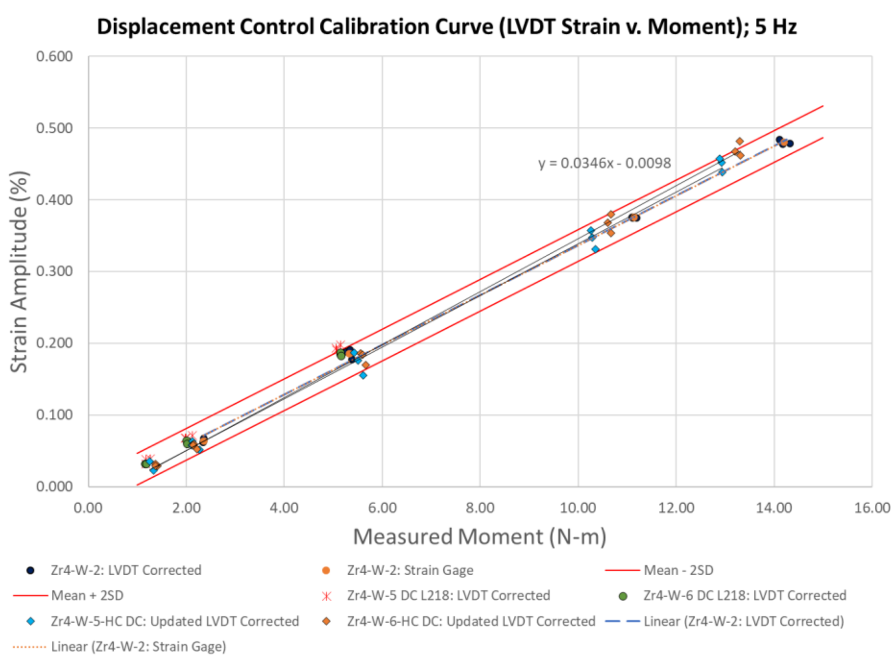

Figure F3-3. The calibration curve provided in Figure F3-1 compared to the hot cell displacement-controlled CIRFT data at 5 Hz using the updated dynamic correction factor of 1.0; LVDT Corrected is the strain amplitude from that LVDT measurements including the standard corrections [F3-1].

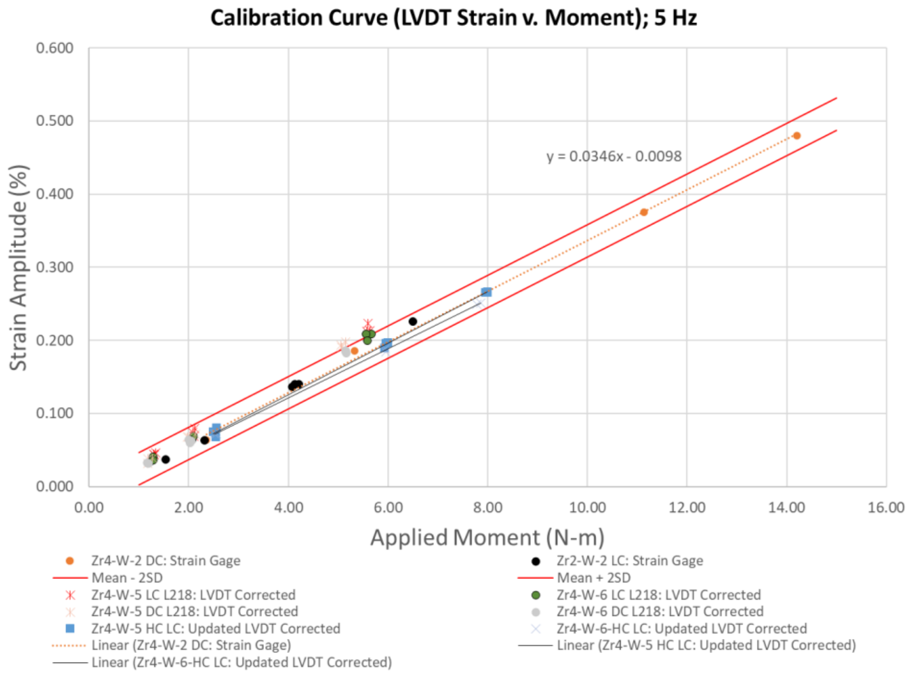

Figure F3-4. The calibration curve provided in Figure F3-1 compared to the hot cell load-controlled CIRFT data at 5 Hz using the updated dynamic correction factor of 1.0; LVDT Corrected is the strain amplitude from that LVDT measurements including the standard corrections [F3-1].

F3-4.1. The Dynamic Correction Factor for Fuel Rod Data

The observation that the dynamic correction factor for hot cell CIRFT is 1.0 rather than ~0.82 [F3-1] suggests a conservative bias in CIRFT data previously reported and used by the NRC and ORNL to develop fatigue design curves for high-burnup fuel rods. The magnitude of the conservatism can be calculated for the fatigue (or endurance) limit, which is ~0.06% on a best estimate bases or ~0.03% on a design basis [F3-9]. Assuming a dynamic correction factor of 1.0, the best estimate fatigue limit would increase to only ~0.07%, and the design limit would increase to ~0.036%. This is a relatively small change and within the uncertainty of ± 0.022%. In addition, the bias is conservative and would therefore cause no safety concerns even if it were not adjusted. Thus, it is acceptable to continue to apply the dynamic correction factor as defined previously [F3-2], [F3-3] to the CIRFT data collected on irradiated fuel rods in the ORNL hot cell.

F3-5. SUMMARY AND CONCLUSIONS

The calibration of the hot cell CIRFT was confirmed by comparison to the calibrated out-of-cell CIRFT system because the load cells and LVDTs in the hot cell cannot be directly calibrated [F3-1]. A key part of the calibration process was the use of the uncertainty in the LVDT-based strain amplitude in the out-of-cell CIRFT as the acceptance criterion for the hot cell CIRFT. The uncertainty in the strain amplitude was defined as two times the standard deviation of the LVDT-based strain amplitude relative to the measured strain amplitude from a strain gauge. The uncertainty in the strain amplitude was determined to be ± 0.022%.

In addition, during the calibration of the hot cell CIRFT, it was determined that the dynamic correction factor used in processing the data is 1.0 rather than the value used previously (~0.82, [F3-2]). This suggests that there is a small conservative bias in the previously reported strain amplitudes for high-burnup fuel rods.

However, because this bias results in a conservative change in the reported strain amplitude that is within the uncertainty, the previous dynamic correction factor (~0.82) remains acceptable for calculation of strain amplitude when fatigue testing irradiated fuel rods in the hot cell CIRFT.

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