ENCLOSURE 2

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Revision 5 of NEDO-33798 Supplement 1, "NSF Channel Annual Experience Summary Report"

Non-Proprietary Information

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Global Nuclear Fuel

NEDO-33798 Supplement 1
Revision 5
February 2022

Non - Proprietary Information

NSF Channel Annual Experience Summary Report

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REVISION SUMMARY

Revision	Revision Description
0	2016 Initial Release
1	2017 Initial Release
2	2018 Initial Release
3	2019 Initial Release
4	2020 Initial Release
5	2021 Initial Release

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SUMMARY

This annual report for 2021 provides a summary of the ongoing experience with Global Nuclear Fuel's (GNF's) NSF channels as required by the Nuclear Regulatory Commission's (NRC's) conditions and limitations that are stipulated as a condition for the licensing of NSF channel material in reload quantities. The planned operation of five of the six US NSF mini-batches have finished and their discharge inspection requirements have now been fulfilled.

New poolside inspections of 144 NSF channels from six Boiling Water Reactors (BWRs) operating in the United States (US) have been completed between November 2020 and July 2021. New measurements of channel bow and length add to the experience base and continue to demonstrate the expected low distortion and low growth behavior for NSF channels. A previously unrecognized incompatibility of GNF's SimCHAD system to measure non-GE14 channel bulge accurately was identified; thus, reporting of new GNF2 and GNF3 bulge measurements are deferred to 2022 when corrective actions will be completed, and seven measurements first reported in 2020 have been temporarily retracted. New corrosion measurement data using FSECT are reported, which demonstrate stable corrosion behavior to high exposure, end of life conditions.

All conditions and limitations of the NSF Licensing Topical Report (LTR) Safety Evaluation (SE) that require annual reporting are met by this report.

ACRONYMS

Acronym	Explanation
BWR	Boiling Water Reactor
CFM	Cell Friction Metric
CHAM	CHAnnel bulge Measurement system
ECBE	Effective Control Blade Exposure
EOC	End-of-Cycle
FSECT	Frequency Swept Eddy Current Technique
GNF	Global Nuclear Fuel
GNF-A	Global Nuclear Fuel - Americas
LTR	Licensing Topical Report
LUA	Lead Use Assembly
LUC	Lead Use Channel
NRC	Nuclear Regulatory Commission
NSF	Zr-Sn-Nb-Fe Alloy
PWR	Pressurized Water Reactor
R-factor	Weighted rod power local peaking for critical power calculations
SE	Safety Evaluation
SIMCHAD	Simplified Channel Dimensional Measurement Device
US	United States

1.0 INTRODUCTION

Global Nuclear Fuel (GNF) proposed the use of its NSF[1] channel material as a material solution that could mitigate channel to control blade interference that emerged in the early 2000s as an operational concern. The benefit of NSF arises from its resistance to both fluence gradient-induced bow and shadow corrosion-induced bow. GNF loaded NSF Lead Use Channels (LUCs) in several United States (US) and European Boiling Water Reactor (BWR) plants starting in 2002 to gain experience with the material. An expanded LUC program that allowed up to 8% LUCs was approved by the Nuclear Regulatory Commission (NRC) in 2013 (MFN 12-074 Supplement 2-A, Reference 1).

Approval of the 8% LUC program included Condition and Limitation 3 to visually inspect and measure the length[2] of [[ ]] of the LUCs during each outage, and upon discharge to visually inspect and measure the length of [[ ]] of the LUCs and to measure the distortion (bow and bulge) of [[ ]] of the LUCs. The NRC approved the batch application of NSF channels in September 2015 (MFN 15-076, Reference 2). The expanded NSF LUC program monitoring and inspection plan, detailed in Section 3.2 of the MFN 12-074 Safety Evaluation (SE) report, must be completed as a requirement of the batch application approval. In addition, the batch approval requires the submittal of an annual NSF experience report to the NRC to ensure continued in-reactor performance and applicability of NSF models.

1.1 PURPOSE

The purpose of this report is to provide an annual NSF experience report to satisfy NRC requirements set forth in the SE report as a condition for the licensing of GNF's NSF channel material in reload quantities as specified in MFN 15-076 (Reference 2).

1.2 SCOPE

The scope of this NSF annual experience report provides a summary of the specific items that are required to be reported as set forth in the SE in Condition and Limitation 4 (Reference 2). These required items are the following:

a. Plot of NSF channel irradiation database expressed as Effective Control Blade Exposure (ECBE) versus exposure.
b. Plot of measured channel growth versus fast neutron fluence data, along with NSF growth model predictions.
c. Plot of measured channel bulge versus exposure data.
d. Plot of measured channel bulge data versus NSF channel bulge model predictions.
e. Plot of measured channel distortion (total) versus exposure data, segregating low and high ECBE data.

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[1] NSF derives its name from the alloying elements used in a new channel material developed by GNF; Zr-Nb-Sn-Fe.
[2] Length measurements are used to determine the channel growth.

f. Plot of inferred shadow bow versus ECBE data, along with NSF shadow bow model predictions.

In addition, in response to RAI-10 of the NSF LTR (Reference 2), GNF committed to measuring NSF channel oxide thickness on ~20 high exposure bundles (~6 and ~8-year residence time) to confirm the oxide thickness. To achieve this, GNF has purchased a non-destructive eddy current-based system known as FSECT (Frequency Swept Eddy Current Technique), developed by EPRI (Electric Research Power Institute), and adapted it for poolside use on GNF channels.

Since the 2020 annual report was issued (Reference 3), the new data available for items a through f, above, are channel distortion measurements of 144 channels from four US BWR6 S-Lattice and two BWR4 C-Lattice plants. All plots for items a through f are provided in this annual report and a new plot is included that summarizes FSECT corrosion measurements of 22 channels.

SE Condition and Limitation 5 (alterations to distortion models), 6 (elimination of channel-control blade interference counter measures), and 7 (changes in R-factor uncertainty) specified in Reference 2 require reporting when changes have been made. Because no changes were made in this annual reporting cycle, they are not included herein. In addition, channel corrosion measurements of 22 NSF channels using an eddy-current based system called FSECT are reported, thereby fulfilling GNF’s commitment made in RAI-10 of the NSF LTR (Reference 2).

2.0 NSF CHANNEL INSPECTIONS AND PERFORMANCE

2.1 INSPECTIONS

New US poolside inspections of NSF channels from four US BWR6 S-Lattice and two BWR4 C-Lattice plants, categorized as LUCs, LUAs, and mini-batches, have been completed since the 2020 annual report (Reference 3). Inspection of these channels included bow and bulge measurement, using GNF's SimCHAD (Simplified CHAnnel Dimensional) measurement system, on all 144 channels, CHAM (CHAnnel bulge Measurement) system for bulge on 2 channels, visual and length on 55 channels, and FSECT for corrosion on 22 channels from among the same 144 channels. The inspected quantities of the mini-batches met the licensing inspection requirements.

The US inspections included in this report are summarized in Table 2-1, and details of the inspected channels are summarized in Table 2-2, which include a range of exposure and ECBE conditions. Currently, the irradiated NSF SimCHAD data, CHAM data, and length measurement data encompasses the burnups and ECBEs shown in Figure 2-1 (Condition and Limitation 4.a). The database is bounded with [[ ]] channel exposure and [[ ]] ECBE.

2.2 PERFORMANCE

The measured growth, creep bulge, total distortion, and inferred shadow corrosion bow for NSF channels are summarized in the following sections. Comparisons are made to Zircaloy-2 in some cases to show the broader context in which the data exist.

2.2.1 NSF Channel Growth

Consistent with Condition and Limitation 4.b, NSF channel growth measurements, based on a calibrated tape measure, are shown in Figure 2-2 as a percentage change from the nominal original length. The data shows that NSF growth is trending with fluence above and below the current model line and does not indicate that NSF's distortion model requires modification. At high fluence, the population of NSF channels continues to [[ ]] channels that start to exhibit signs of breakaway growth initiation between [[ ]] fast fluence.

2.2.2 NSF Channel Creep Bulge

Consistent with Condition and Limitation 4.c, the measured channel creep bulge based on SimCHAD as a function of exposure is shown in Figure 2-3 for 100T NSF channels, in Figure 2-4 for 120T NSF channels, and in Figure 2-5 for GNF3 Lead Use Assembly (LUA) 93/63 NSF channels. Data are plotted for the [[ ]] inch elevations. In addition, bulge measurements based on CHAM for the [[ ]] inch elevations are included in Figure 2-5 for the GNF3 LUAs. NSF creep bulge is [[ ]] based on the available data which, importantly, includes new data for high exposure channels that operated for four 2-year cycles. Maximum bulge is approximately [[ ]], with most bulges being less than [[ ]]. The new GNF2 and GNF3 SimCHAD-based bulge measurements that are being deferred temporarily, also exhibit normal, stable behavior when a preliminary correction is made to account for the small tilt bias.

Consistent with Condition and Limitation 4.d, the measured bulges compared to predicted values at the [[ ]] inch elevations are shown in Figures 2-6 and 2-7 for 100T and 120T NSF channels, respectively. The model tends to predict bulge reasonably well for the available data, thus no changes to the NSF bulge model are warranted.

2.2.3 NSF Channel Total Distortion

Consistent with Condition and Limitation 4.e, the measured total distortion as a function of exposure for NSF channels is shown in Figure 2-8. New GE14, GNF2, and GNF3 data are included in Figure 2-8. NSF's total distortion is [[ ]] about the zero-distortion axis between [[ ]]. NSF total distortion is [[ ]] and less variable compared to that of Zircaloy-2 channels, for a wide range of plants and operating conditions.

2.2.4 NSF Channel Inferred Shadow Corrosion Bow

Consistent with Condition and Limitation 4.f, the inferred shadow corrosion bow data from NSF channels in S-Lattice and C-Lattice plants are plotted versus ECBE in Figure 2-9. New GE14, GNF2, and GNF3 data are included in Figure 2-9. The NSF data is segregated into exposures less than [[ ]] and greater than [[ ]]. A comparison of NSF's inferred shadow corrosion bow data to its current S120T/C100T NSF shadow corrosion bow model, shown in Figure 2-9, demonstrates that there is good agreement between the model and data and therefore no modifications to the NSF shadow corrosion bow model are warranted. A comparison of NSF's shadow corrosion bow data to Zircaloy-2 channels for exposures greater than [[ ]] is also provided in Figure 2-9, which demonstrates that NSF has superior shadow corrosion bow performance relative to Zircaloy-2.

NSF D-Lattice data is also shown in Figure 2-9, which includes only [[ ]]. As with [[ ]], the D-Lattice and S-Lattice/C-Lattice NSF models are [[ ]]. The NSF D-Lattice model is [[ ]] D-Lattice model, and the NSF D-Lattice and S-Lattice/C-Lattice models are [[ ]] over most of the ECBE range due to the [[ ]]. Near the [[ ]] ECBE saturation point, the S-Lattice/C-Lattice and D-Lattice NSF models diverge about [[ ]] but are much closer to each other at [[ ]]. The [[four]] channels in the NSF D-Lattice population are bounded by either the [[ ]], and with such [[ ]]

2.2.5 NSF Channel Corrosion

Outer surface oxide thickness measurements were made using FSECT on ten GNF2 mini-batch channels from River Bend and ten GNF2 mini-batch channels from Limerick 2, which all operated nominally for ~6 years (3X nominal 2-year cycles). In addition, measurements were made on two GE14 LUC channels from Limerick 1 that operated nominally for ~8 years (4X nominal 2-year cycles). Ten measurements were taken on each of the four sides of each channel at ten standard

elevations spanning 7-127 inches, as well as other selected positions. Approximately 1000 measurements were made in total. Total thickness averages and standard deviations were calculated representing each group of 2 or 10 channels from the three plants. The averages and standard deviations were then added to Figure 3d-1 that was included in the NSF LTR (Reference 2), which is now shown updated as Figure 2-10 in the present report. The FSECT data show stable corrosion behavior of NSF channels out to high exposure, end of life conditions. GNF's minimum licensing commitment to validate NSF channel corrosion is now satisfied.

Table 2-1 NSF 2019-2020 Channel Inspections (Plants and Classifications)

Plant	Plant Type	Number of Channels in Program	Use Classification	Last Operating Cycle #/Date	Inspection Date
[[					
					]]

*3 channels discharged earlier

**2 channels discharged earlier

Table 2-2 Operating History Summary of NSF Channels Inspected in 2020-2021

Plant	Use Classification	No. of Inspected Channels	Inspection Scope	Range Bundle Exposure (GWd/MTU)	Range ECBE (inch-days)	Fuel Design
[[	Mini-batch	24	SimCHAD	[[		GNF2
	Mini-batch	10*	Visual, Length			GNF2
	Mini-batch	32	SimCHAD			GNF2
	Mini-batch	13*	Visual, Length			GNF2
	Mini-batch	24	SimCHAD			GNF2
	Mini-batch	10*	Visual, Length			GNF2
	LUC	5	SimCHAD			GE14
	Mini-batch	25	SimCHAD			GNF2
	Mini-batch	10*	Visual, Length, FSECT			GNF2
	GNF3 LUA	2	SimCHAD, CHAM			GNF3
	Mini-batch	30	SimCHAD			GNF2
	Mini-batch	12*	Visual, Length			GNF2
	Mini-batch	10*	FSECT			GNF2
]]	LUC	2	SimCHAD, FSECT		]]	GE14

*From among SimCHAD group

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Figure 2-1 Range of Exposure and ECBE for Irradiated NSF Channel Distortion and Length Measurement Database

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Figure 2-2 GNF Channel Growth Data and NSF Irradiation Growth Data

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Figure 2-3 Measured Creep Bulge versus Exposure for NSF 100T Channels

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Figure 2-4 Measured Creep Bulge versus Exposure for NSF 120T Channels

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Figure 2-5 Measured Creep Bulge versus Exposure for NSF 93/60 Channels

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Figure 2-6 Measured Creep Bulge versus Predicted Creep Bulge for NSF 100T Channels

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Figure 2-7 Measured Creep Bulge versus Predicted Creep Bulge for NSF 120T Channels

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Figure 2-8 Measured Total Channel Distortion versus Exposure for NSF and Zircaloy-2 Channels

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Figure 2-9 Plot of Inferred Shadow Bow versus ECBE for NSF and Zircaloy-2 Channels

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Figure 2-10 NSF FSECT Corrosion Measurements Compared to Upper bound Design Values

For Corrosion and Hot Cell Oxide Thickness Data for NSF and Zircaloy-2 (Data Points Represent Single Channel Average or Multiple Channel Campaign Average with Multiple Measurements from Channel Elevations and Sides; Uncertainty bars represent one standard deviation).

3.0 REFERENCES

1. Letter, Andrew A. Lingenfelter (GNF) to Document Control Desk (NRC), "Accepted Version of Enhanced Lead Use Channel (LUC) Program for NSF Fuel Bundle Channels," MFN 12-074 Supplement 2-A, April 15, 2013.

2. Letter, Brian R. Moore (GNF) to Document Control Desk (NRC), "Approved Version of NEDE-33798P Revision 0, 'Application of NSF to GNF Fuel Channel Designs'," MFN 15-076, September 30, 2015.

3. Letter, Brian R. Moore (GNF) to Document Control Desk (NRC), "NEDE-33798P Supplement 1, Revision 4, 'NSF Channel Annual Experience Summary Report'," M200144, October, 2020.