GNF Fuel Reliability and Channel Performance: 2018 Update

R. SCHNEIDER, D. LUTZ, P. MCCUMBEE, P. CANTONWINE

Global Nuclear Fuel-Americas, LLC, Wilmington, NC 28401
Phone: +1 910 524-3581 e-mail: paul.cantonwine@gnf.com

ABSTRACT

The two main performance issues in BWR fuel are failure of fuel rods by debris fretting and channel-control blade interference. Debris fretting remains the only confirmed mechanism to cause failures in GNF2 fuel. Failures from manufacturing defects, primary hydriding, corrosion, and PCI have not been observed. The lack of failures from fabrication-related problems is a testament to the outstanding manufacturing practices at GNF as well as to the robust design of the fuel. The prevention of PCI failures has been from advances in pellet quality, core designs, and customer adoption of the GNF fuel operating guidelines. To improve the resistance to debris failures, GNF introduced GNF2.02 in 2016. GNF2.02 has a modified Defender^{TM} filter, which increased the debris capture capability of the small wire-like debris that is still causing failures, and a modified spacer, which eliminated some debris capture sites. The introduction of GNF2.02 went from concept to implementation in one year – an example of the kind of rate of innovation our industry needs. Longer-term, GNF expects a full transition to GNF3, which was designed to further improve fuel reliability while also increasing fuel-cycle benefits over GNF2.

Observations of channel-control blade interference continue with the use of Zircaloy-2 and Zircaloy-4 channels. The most recent observations have been with Zircaloy-4 channels, which supports GNF's view of this material as an interim solution until the full introduction of NSF channels is complete. NSF channels have been performing as expected with no observations of channel-control blade interference.

Keywords: BWR fuel, fuel reliability, channel distortion

1. Introduction

As GNF looks ahead at innovations in fuel technology, the view is always based on a good understanding of the performance of operating fuel [1-3]. That understanding provides a clear picture of what is working and where innovations are needed. The purpose of this paper is to provide an update to the fuel reliability and channel performance of GNF fuel designs for BWR applications. The focus of the discussion will be the fuel performance of GNF2 and actions taken to make this the most reliable GNF fuel design to date. Those actions include improving debris resistance and providing guidance to avoid PCI failures. Looking ahead at GNF3, GNF is continuing to develop filter technologies for the lower tie plate and debris resistant coatings. In addition, there continue to be performance issues with both Zircaloy-2 and Zircaloy-4 channels. A summary of those issues is provided with an update on the introduction of NSF channels, which is expected to eliminate channel – control blade interference as a performance issue. NSF is a Zr-Nb-Sn-Fe alloy with a nominal composition of 1.0% Nb, 1.0% Sn, 0.4% Fe and Zr in balance.

2. GNF2 Fuel Reliability

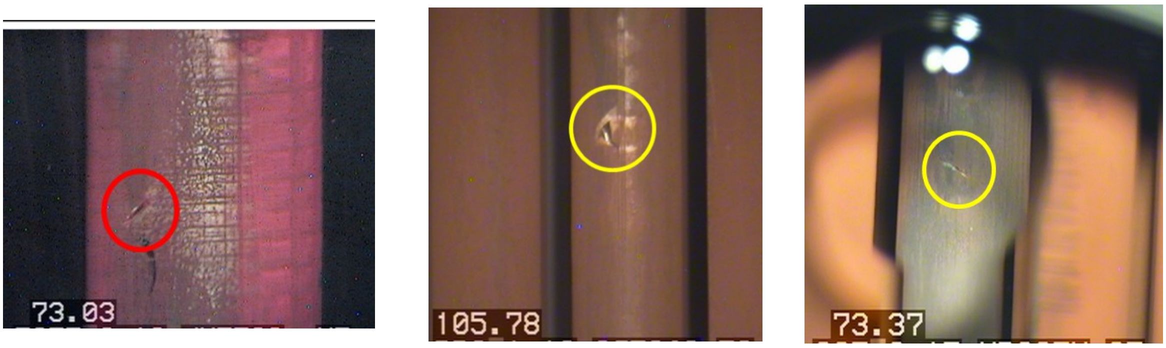
Approximately 75% of all GNF fuel in operation in the fleet is now GNF2. In terms of number of rods operated, GNF2 is the second-largest design in the GNF experience base, at ~1.7 million as of spring 2018. Only GE14 (at ~3.4 million rods) has more operating experience. GNF2 has operated under "all existing" BWR conditions and operating modes, as well as the entire fleet range of power density, cycle length (12-18-24 months), and water chemistry (Normal Water Chemistry to On-line Noble Chemistry - OLNC.) There are no confirmed failures from manufacturing defects, corrosion (including shadow corrosion), or PCI. The lack of failure from manufacturing defects and corrosion are attributed to the quality of the manufacturing process and manufacturing specification for the Zircaloy-2 cladding. PCI has been mitigated by operational guidelines as discussed in Section 5. The only mechanism to cause failures in GNF2 has been debris fretting. Just like in GE14, a large percentage of the debris failures are concentrated in a small number of plants that have higher power densities with pumped-forward feed-water heater drains and most with no strainers in the feedwater (FW) or heater-drain system. In cascade-drain plants, most failure events appear to correlate well with component failures in service or on-line maintenance.

3. GNF2 Inspection Observations

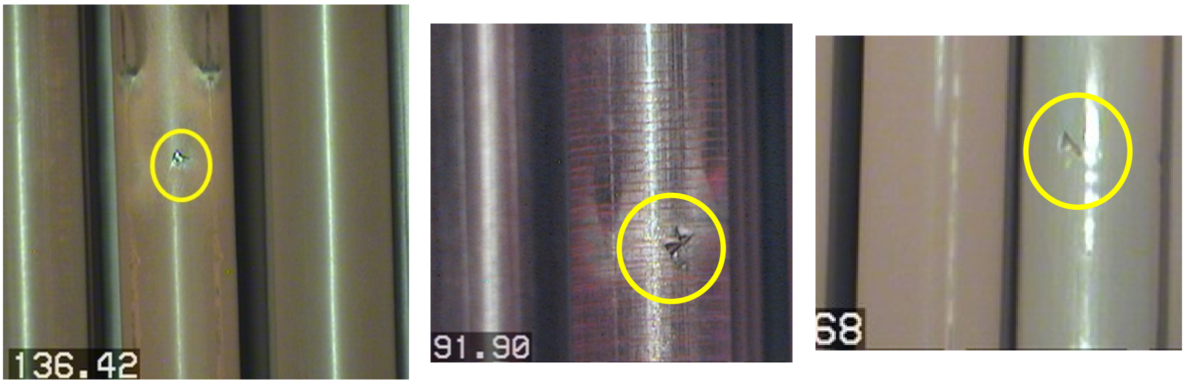
All GNF2 failures discharged have been inspected, and only debris fretting has been found to cause failures. Another big benefit of the GNF2 design has been an elimination of instances of spacer-channel interference at high exposure/residence time which was a lifetime-limiting phenomenon in GE14 with Zircaloy-2 spacers.

Fig 1 shows several examples of debris fretting perforations that have been identified in GNF2. As with prior fuel designs, all fretting perforations occur at/under fuel assembly spacers, and the debris perforations are biased into the upper half of the bundles where flow-induced vibration (FIV) conditions are more conducive to fretting. Based on the correlation of debris failures occurring in pump-forward drain plants or in cascade-drain plants after component failure or on-line maintenance, it is clear that debris causing failures is entering during normal operation through the lower tie plate filter at the bottom. Note, all six photographs are from under-spacer areas, and there is no evidence of elevated shadow corrosion in any. These photographs cover a range of chemistry conditions and crud levels (FW Fe inputs from < 0.1 ppb to ~2.5 pbb)

Fig 2 shows several examples of debris caught in the notches of the spacer bands in GNF2. This observation has been incorporated into the fuel design in two ways as discussed in section 4.0.

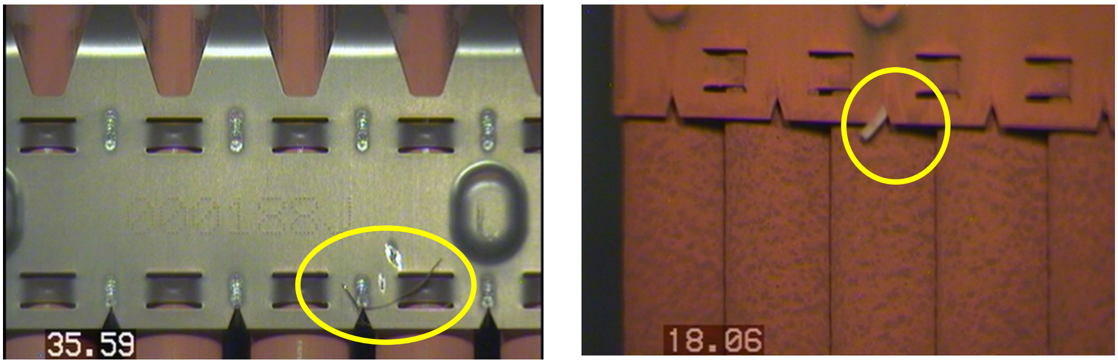


At Spacer 4 At Spacer 6 At Spacer 4



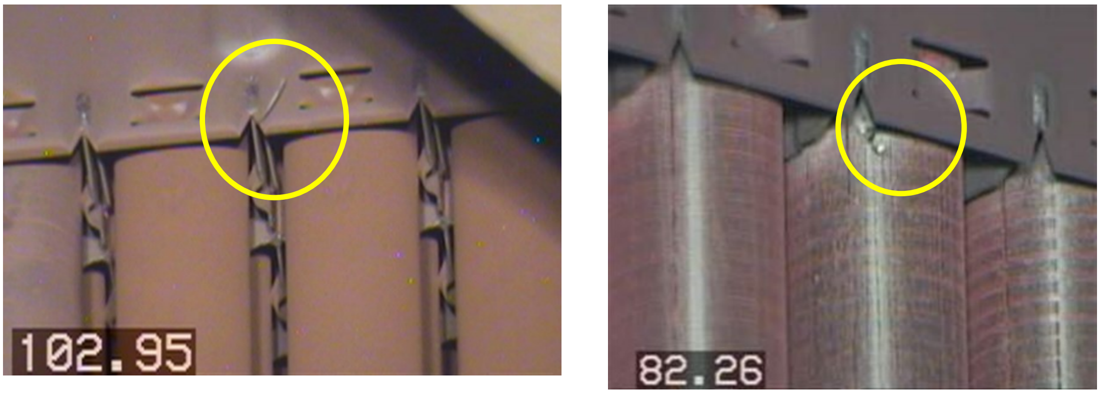
At Spacer 8 At Spacer 5 At Spacer 8

Fig 1. Examples of debris fretting perforations that have been identified in GNF2.



Long thin wire caught at spacer 2 (from bottom.) Did not cause fuel rod failure. Wire removed, bundle reinserted for additional cycles, did not fail. Note fretting wear on spacer band from tips of wire

Metal Strip caught at spacer 1. Did not cause fuel rod failure. Debris removed, bundle reinserted for additional cycles, did not fail.



Wire in Spacer 6. No failure here, but a different rod at a lower elevation spacer in the bundle had a debris fret perforation. Wire removed, bundle discharged due to leaker rod.

Fuel rod failure, debris no longer present at time of inspection. Rod replaced, bundle reinserted, operated multiple cycles, no failure.

Fig 2. Examples of debris caught in the notches of the spacer bands in GNF2

4. Debris Mitigation

Given the observations of debris failures in plants with GNF fuel and recognizing that debris excursions will occasionally occur even in plants with the best foreign material exclusion programs, GNF has continued to develop debris mitigating technologies. In 2016 GNF made improvements to the Defender^{TM} filter and the spacers in the GNF2 design and rebranded the design, GNF2.02. Currently, GNF is developing an advanced next-generation filter technology for the GNF3 lower tie plate and debris resistant coatings for our Zircaloy-2 cladding, which appears to also offer improved oxidation resistance.

The motivation for the changes to GNF2 was a larger than normal number of debris failures in 2015. While GNF was working on an advanced next-generation filter at that time, it became clear that more near-term action was needed. In late 2015, GNF initiated a project to improve GNF2's resistance to debris failures. Because the objective was to implement an improvement as quickly as possible, the scope of the change was limited to altering the components of the Defender^{TM} filter in a way that mitigated debris but did not affect any other performance requirement, especially pressure drop, and was still considered within the licensing basis for GNF2. The ideas for the change were based directly on the observations of debris capture in the spacers.

Utilizing the rapid prototyping capabilities of 3D printing and debris-capture effectiveness testing developed while working on an advanced next-generation filter, various filter designs were fabricated and tested. The initial results were encouraging. In a matter of three months, a design was down selected and fabrication of prototypical filters was initiated. In the next six months debris-capture effectiveness and pressure drop testing were performed to confirm design requirements were met. The new Defender Plus filter provided a factor of 2 improvement in the capture of the smallest debris sizes (wires sizes like those observed in Fig 2) while maintaining the pressure drop. In less than a year the new Defender Plus filter was in production and ready for reload applications in 2017.

In parallel to the development of the Defender Plus filter, changes to the spacer design were made to eliminate the notches on the band. There were no significant technical issues in removing these features in the spacer because the change did not affect the pressure drop characteristics of the spacer. However, because the notches had originally been added to the spacer as a manufacturing aid, significant effort was required on the supplier side (new tooling and requalifications) to support the reload application schedule.

After the launch in early 2017, GNF2.02 was rapidly adopted by most of the GNF customer base. As of late 2017, almost every customer using GNF2 has transitioned to GNF2.02, and the in-reactor performance has been encouraging, recognizing that all GNF2.02 reloads are still in their first cycle of operation.

Once the design of the Defender Plus filter was complete, it was recognized that further improvement was desired for GNF3. Thus, work on improving the debris-capture effectiveness of the lower-tie-plate filter continued. The goal of this next-generation filter is to increase debris-capture effectiveness another factor of 2 or 3 for the very small debris sizes being observed to cause failure. As with the development of Defender Plus, it is desired to improve debris-capture effectiveness while not impacting pressure drop. The status is that a new filter technology has been identified that offers the potential to meet all design requirements.

While improvement of the lower-tie-plate filters is the most expedient way to improve debris mitigation, experience indicates that filters will not be 100% effective. Thus, to eliminate debris failures altogether, GNF has been developing a debris-resistant coating (called ARMOR^{TM}) that can be applied either just around the spacers or over the full length of the fuel rod. The out-of-reactor testing has been encouraging enough that lead-test assemblies with ARMOR^{TM} coated fuel rods were inserted in a US plant in 2018 [4].

5. PCI Mitigation

Failures from pellet cladding interaction (PCI) began to occur in the 1970s. With the introduction of barrier fuel in the 1980s by GE Nuclear Energy, there was a large positive step change in fuel reliability and in plant operation – a reduction in PCI failures with a simultaneous improvement in the capacity factor for plant maneuvering. Despite these improvements, by the mid 1990's it became clear that certain types of operation correlated with low-level PCI-type failures in 8x8 liner fuel. Very long control intervals and rod pulls at or near rated power were common elements in failure events; and the role of pellet quality in reducing the threshold to PCI-type failures was established, leading to improved pellet specifications.

PCI-type failures in barrier fuel decreased by another order of magnitude by the early 2000's with higher array fuel designs, lower LHGRs, shorter sequences in conventional core 24-month cycles, and the aforementioned pellet quality improvements. Several PCI-type failure events in the mid-2000's in GE14 10x10 fuel and industry goals to drive failures to zero (to the extent practical) led to the first formal PCI guidelines for barrier fuel, which included explicit consideration of PCI risk factors in bundle, core, and rod pattern designs. The GNF Fuel Operating Guidelines, first issued in 2006, have been revised several times to reflect the latest operational experience while retaining a balance between the effectiveness in preventing failures (~100%) with minimal capacity factor impact (less than 1 EFPD in most 24-month cycles). GNF2 fuel has benefitted from all of these developments; it is not a coincidence that no PCI-type failures have occurred in the design, despite high duty applications in uprated 24-month cycles as well as extensive operation to ~7.5 year residence times in lower power density plants.

GNF3 fuel uses the same rods as GNF2 and it is fully expected that the same zero-leaker performance will be achieved using similar Operating Guidelines. GNF intends to evaluate the performance of GNF3 in the transition cycles and as always, will explore opportunities to further optimize the guidelines and core monitoring software to balance the reliability and capacity factor goals of the fleet.

6. Channel Interference Observations

In addition to fuel rod failures causing operational issues, channel – control blade interference caused by channel distortion-induced friction continues to be an operational concern in BWR plants (see Fig 3). Observations of interference occur when the control blade fails to settle (“no-settle”) into a notch within 30 seconds (there are 48 notches from full-out to full-in). Initially the observations were a result of distortion problems with Zircaloy-2 channels that were controlled early in life, and thus susceptible to shadow corrosion-induced bow. Discharge exposures greater than 45 MWd/kgU also contributed to greater fluence-gradient induced bow.

Many of the recent observations of cell friction (channel-control blade interference) are occurring in cells that contain Zircaloy-2 and Zircaloy-4 channels. These no-settles are occurring very late in 24-month cycles and often involve bundles that had early life control (shadow corrosion). Control of fresh fuel is a characteristic of very high-energy 24-month fuel cycles that is an unavoidable outcome of the high-energy core design strategy. Core designs using GNF’s cell friction methodology and selected use of rechanneling have greatly reduced the incidents of inoperable control blades, the number of cells experiencing increased friction, and the surveillance burden on plants, even as plant capacity factors have improved and bundle exposure has increased. But it has not been possible to completely eliminate low-level friction indications late in cycles at maximum exposures with Zircaloy channels. A new channel bow resistant material is needed to take another step change in eliminating the occurrence of channel – control blade interference. That material is NSF.

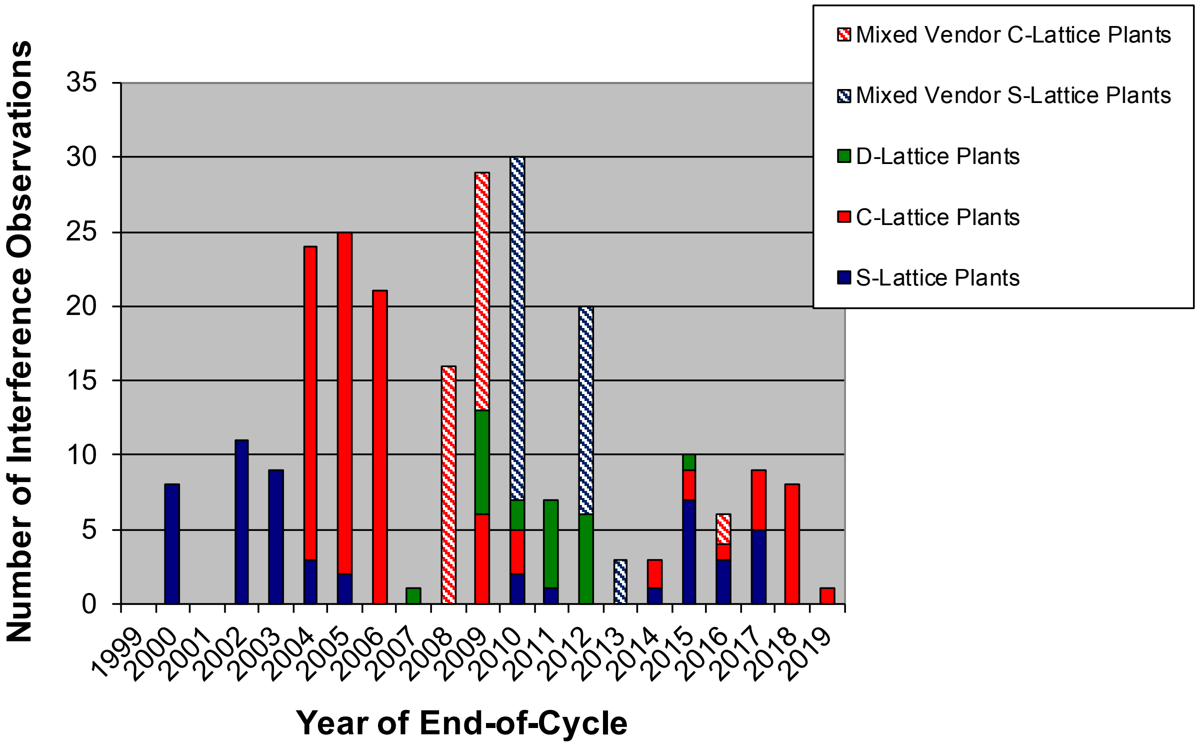


Fig 3. Observations of interference in Boiling Water Reactors with GNF fuel. The time axis is in terms of the year when the cycle ends rather than in terms of when the observations were made.

7. NSF Channel Performance

NSF is a Zr-Nb-Sn-Fe alloy with a nominal composition of 1.0% Nb, 1.0% Sn, 0.4% Fe and Zr in balance. NSF is resistant to both fluence gradient-induced bow and shadow corrosion-induced bow. NSF is resistant to fluence bow because it is resistant to breakaway irradiation growth, in contrast to Zircaloy-2 and Zircaloy-4. Irradiation growth data from BOR60 indicates that NSF does not exhibit breakaway characteristics out to a fluence more than twice the typical end-of-life (EOL) fluence in a channel [5]. In contrast to NSF, Zircaloy-2 exhibits breakaway growth at fluences that can range from 6E+21 to 9E+21 n/cm^2 [5], which results in significant variability in channel growth at EOL fluences. This variability in channel growth translates to a large uncertainty in bow of Zircaloy-2 channels, and to a lesser extent Zircaloy-4, at high exposures. NSF is also more resistant to shadow corrosion-induced bow compared to Zircaloy-2 and Zircaloy-4. NSF experiences shadow corrosion, but it is the side-to-side difference in hydrogen content from shadow corrosion that causes shadow bow. NSF has a lower hydrogen pickup fraction than Zircaloy-2 [5-6], which renders it more resistant to bowing with less variability.

Bow variability is an underlying factor in the on-going interference observations depicted in Fig 3. Measured values of Zircaloy shadow bow[1] can be as much as 5 mm above or below the nominal model prediction line, which is distinctly more than NSF's variability as shown in Fig 4. Since the available gap between the channel and control blade is small, the high variability in shadow bow data means that it should be expected that a few Zircaloy channels per year will occasionally contribute to outlier interference behavior. In addition to the lower measured bow, the lack of variability in the NSF data should make it possible to eliminate

---

[1] Shadow bow is calculated as measured bow minus predicted fluence bow.

observations of channel – control blade interference, once reload quantities of NSF channels reach the 2nd and 3rd cycles.

Currently there are over 5000 NSF channels in operation. None of the interference observations summarized in Fig 3 are attributed to NSF, and results of the on-going inspections continue to exhibit the expected low bow behavior. As more NSF channels are operated and measured for channel distortion at discharge exposures, NSF data that exhibits less variability as indicated in Fig 4 will enable finer calibration of GNF's channel-to-control blade friction model and thereby further improve its predictive capability.

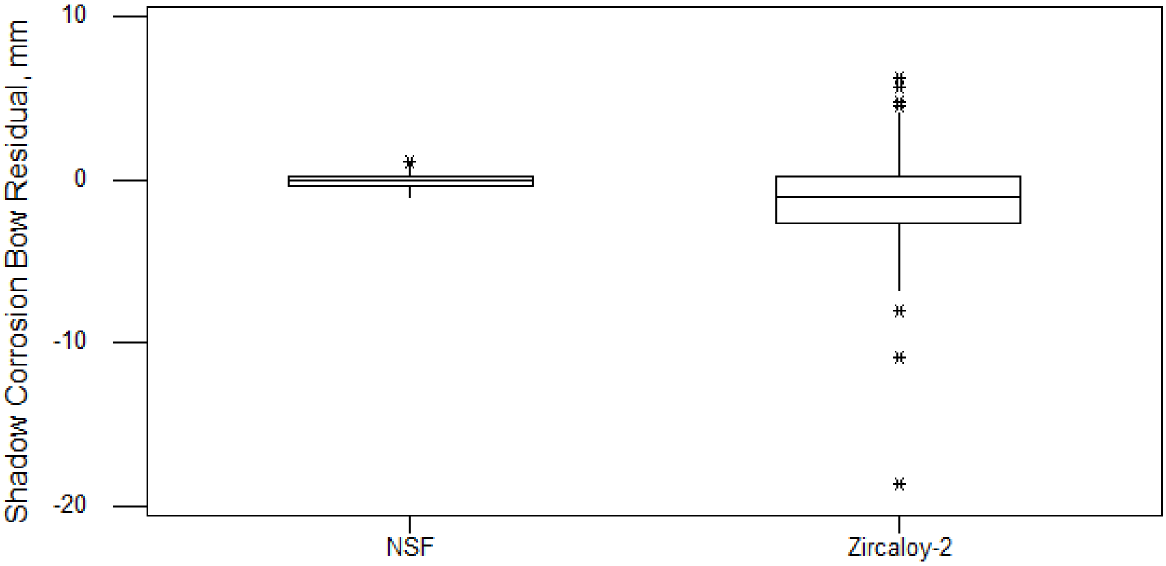


Fig 4. Box and whisker plot of shadow corrosion bow residual (difference between measured value and predicted value) of NSF and Zircaloy-2 channels in BWR S lattice plants and BWR C lattice plants. Plot depicts median, first and third quartiles, upper and lower limits, and outliers.

8. Summary

GNF continues a strong inspection program of current operating fuel. Based on these observations, GNF2 is currently the most reliable fuel design in GNF history. The only mechanism known to cause fuel failures in GNF2 is debris fretting. PCI failures have been mitigated with the application of the GNF PCI guidelines. Going forward, fuel reliability is expected to improve with the implementation of GNF2.02 with its improved Defender Plus filter and modified spacer to minimize debris capture sites.

Looking ahead at the implementation of GNF3, fuel reliability will improve even more with the eventual implementation of GNF's next-generation filter technology now being developed or the deployment of ARMOR™ coated fuel rods.

Channel – control blade interference continues to be an operational issue for BWRs in the United States. The most recent observations have been associated with Zircaloy-4 channels. One of the reasons interference continues to occur is that there is so much variability in the measured bow of Zircaloy channels – making it difficult to predict performance. Only after NSF channels start to reach their 3rd cycle of operation, does GNF expect the observations of interference to decrease and eventually be eliminated. In addition, if the small variability in the NSF data continues to be observed as more data is collected, the ability to predict interference with NSF channels is expected to improve.

9. References

1) K.L. Ledford, A.A. Lingenfelter, R.J. Schneider, P.E. Cantonwine, M.N. Jahingir, K. Hida, and D.C. Crawford, “GNF Defense in Depth 2010 Update, Proceedings from 2010 LWR Fuel Performance Meeting/TOPFUEL/WRFPM, Orlando Florida, USA, Sept. 26-29 (2010)
2) P. Cantonwine, R. Schneider, R. Dunavant, K. Ledford and R. Fawcett, “GNF Fuel Performance 2015 Update,” Proceedings from TopFuel 2015, Zurich, Swizterland, Sept. 13-17 (2015)
3) R. Schneider, D. Lutz, and P. Cantonwine, “GNF Fuel and Channel Performance: 2016 Update,” Proceedings from TopFuel 2016, Boise, Idaho, USA, Sept. 11-15 (2016)
4) Y-P. Lin, R.M. Fawcett, S.S. Desilva, D.R. Lutz, M.O. Yilmaz, P. Davis, R.A. Rand, P.E. Cantonwine, R.B Rebak, R. Dunavant, and N. Satterlee, “Path Towards Industrialization of Enhanced Accident Tolerant Fuel,” Proceedings from TopFuel 2018, Prague, Czech Republic, Sept. 30 – Oct. 4 (2018)
5) P.E. Cantonwine, D.R. Lutz, D.W. White, and Y-P. Lin, “The Performance of NSF in BWR Conditions,” Zirconium in the Nuclear Industry: 18th International Symposium, ASTM, STP 1597, pp. 909-937 (2018)
6) P. Cantonwine, P. McCumbee, K. Martin, K. Ledford, D. Lutz, R. Fawcett, M. Connor, and S. Desilva, “GNF Fuel Technology Update,” Proceedings from TopFuel 2016, Boise, Idaho, USA, Sept. 11-15 (2016)