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Fuel Reliability:

How it affects the industry, and one fuel vendor's journey to flawless fuel performance

BY ROBERT BUECHEL, VICE PRESIDENT, STRATEGY AND ASIA FUEL OPERATIONS; ADOLFO REPARAZ, MANAGER, PRODUCT PERFORMANCE ENGINEERING; JEFFREY BRADFUTE, VICE PRESIDENT, GLOBAL FUEL ENGINEERING AND PRODUCT MANAGEMENT; AND JEFFERY NORRELL, DIRECTOR, PRODUCT ENGINEERING – ALL EMPLOYEES OF WESTINGHOUSE ELECTRIC CO.

Improving the reliability of nuclear fuel is grounded in a strong nuclear safety culture. The cladding is the primary barrier for fission products, and preserving the integrity of this barrier throughout fuel assembly life is a key fuel element design criterion. Power plants can operate safely with a small number of leaking fuel rods, often called "leakers" in the industry. However, when this primary barrier is breached, gaseous fission products, dissolved radioisotopes, and radioactive particles enter the reactor coolant and are transported to other parts of the plant.

While plants operate safely despite a leaking fuel element, and reactor water chemical cleanup systems continuously remove radioactive material, a leaking rod continues to provide radioisotopes that mix in the coolant and coat other plant surfaces. Leaking rods in a core can result in elevated dose rates during refueling outages and increased total collective dose for the workers in containment, in addition to increased outage costs to deal with the impacts of the leaking fuel assemblies. Once discharged from the core, leaking fuel rods need special consideration and handling for as long as they are in the spent fuel pool. Although one or two leaking fuel rods in a core do not pose a major safety or technical risk, leaking fuel is costly and runs counter to industry objectives for continuously decreasing accumulated worker dose rates. Maintaining operating cores with leak-free fuel reduces radiation doses of industry workers, reduces the operating cost of the plant and promotes acceptance of nuclear energy by the general public.

ACTIONS REQUIRED FOR LEAKING FUEL

Once the presence of a leaking fuel rod in the core is detected, additional diagnostic and chemical analyses need to be conducted during the cycle so that appropriate margin-to-plant operating limits are maintained. The ion exchange beds need to be replaced more frequently. In the case of boiling water reactors (BWRs), control blades are operated to isolate the leaker and suppress the leaking assembly's power. In some cases, if the coolant activity approaches the plant operating limit, the plant undergoes a mid-cycle shutdown to remove the leaking fuel element. During a refueling outage, the identification of the leaking fuel element is done using specialized equipment by a technique known as sipping, where small samples of water or gas are removed above each fuel element and analyzed for the presence of radioactive elements which would indicate the presence of a leaking fuel rod.

Once sipping identifies the leaking fuel assembly, all rods in the impacted assembly are typically interrogated using an ultrasonic pulse to identify the particular leaking rod via the presence of water inside the rod. A leaking fuel assembly can be subsequently repaired by removing the leaking rod and replacing it with a suitable substitute or inert rod, enabling return of the assembly to the core. If repair is not possible, the bundle, and often its symmetric partners in the core, must be excluded from further irradiation, typically resulting in a core redesign. In this case, the unused energy of the sound rods is either not recovered or is deferred to future cycles.

The leaking rod is, in most cases, further inspected to investigate the leaking mechanism. As part of an overall problem identification and resolution process, a root cause analysis (RCA) is conducted, with corrective actions being identified and implemented to avoid recurrence. Follow-up poolside or hot cell post-irradiation examinations (PIE) may be recommended during the RCA, particularly when the leaking mechanism cannot be clearly diagnosed. In some instances, the only definitive way to assess leaking rod causality is to perform destructive cladding and pellet metallographic inspections at a hot-cell laboratory. PIE examinations of leaking fuel rods are often challenged by the presence of secondary degradation in the fuel rod, i.e. further damage after an initial leak. However, even with hot cell destructive examinations, the identification of the root cause may not be possible if the original leaking site cannot be identified due, for instance, to severe secondary degradation.

COST OF LEAKING FUEL

The cost of operating with leaking fuel in the core is significant for both the operating plant and the fuel vendor. Table 1 summarizes some of the most relevant costs associated with operating a plant with leaking fuel. This table identifies different categories of cost and assigns an estimated minimum and maximum range to the cost in U.S. dollars to the plant operator (utility) and the fuel vendor. Differences in the cost associated with a pressurized water reactor (PWR) or BWR are also identified.

FUEL LEAKAGE MECHANISMS

In order to improve fuel reliability, a better understanding of the most prevalent leaking mechanisms is necessary. Westinghouse Electric Co. has obtained an understanding of leaking fuel mechanisms through systematic PIE of both leaking and non-leaking fuel. PIE campaigns of leaking fuel provide a better understanding of the condition of the fuel when the leaker developed. Comparatively, by inspecting non-leaking, discharged fuel, the margin to known-leaking mechanisms, such as grid-to-rod fretting (GTRF) or cladding corrosion, can be quantified. This information can then be used to determine unambiguous causal mechanisms and identify necessary corrective actions.

For light water reactors (LWR), the most significant leaking mechanisms have been: GTRF, cladding crud and corrosion, debris fretting, pellet cladding mechanical interaction, and manufacturing non-conformances. The most prevalent of these for PWRs has been GTRF, followed by debris-induced fretting. With the introduction of new, robust designs, these chronic leaking mechanisms have been eliminated in the reactors that have implemented them.

In BWR reactors, the most prevalent leaking mechanisms have been debris fretting due to foreign material and pellet cladding interaction (PCI) during power ramps. PCI has been essentially eliminated with the use of liner cladding and control of power ramp rates. The most challenging leaking mechanism in BWR fuel continues to be debris fretting, which has required the introduction of fuel design features that are "fine tuned" to trapping most debris before it can enter into the active fuel region, such as modifying spacer grids so smaller debris that passes the filter will not be trapped in the spacer grid to fret against the fuel. BWR bundles are most susceptible to debris-induced failures during their first cycle of operation.

TABLE 1 ESTIMATED COST OF LEAKING CORE OUTAGE

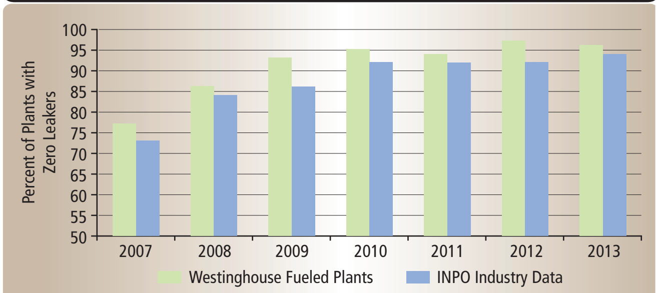
Cost Category	PWR or BWR	Estimated Cost ($K) Utility (1) Min	Utility (1) Max	Vendor Min	Vendor Max
Diagnosis, Tracking, Analysis During Cycle	Both	5	10	10	20
Cost of Sipping during offload	Both	60	100	110	250
Cost of Ultra Sonic Testing (UT) of leaking fuel	Both	40	60	150	250
Cost of repair of leaking fuel	Both	100	150	250	500
Cost due to higher dose rates during outage	Both	60	150	0	0
Cost due to additional maintenance of resin beds	Both	120	180	0	0
Cost due to extended outage	Both	0	3500	0	0
Cost due to unplanned shutdown	BWR	0	3500	0	0
Cost of isolating leaker and suppressing	BWR	40	80	0	0
Cost of Redesign of Core	Both	75	125	0	250
Value of lost energy in fuel	Both	0	150	0	0
Root Cause Analysis	Both	60	120	50	100
Corrective Action Implementation	Both	10	50	20	2500
Root Cause Field Exams	Both	10	30	250	500
Hot Cell Exams(2)	Both	0	500	0	1500

INDUSTRY FUEL PERFORMANCE

In 2006, Jim Ellis, newly appointed president and CEO of the Institute of Nuclear Power Operations (INPO), launched an initiative that raised the profile of the incidence of leaking fuel amongst nuclear operators and vendors. Ellis, the former commander of the U.S.S. Enterprise, was dismayed to learn that fuel failures existed in commercial reactors since there were no fuel failures in military reactors used aboard naval vessels. He challenged the industry to eradicate leakers by 2010. The industry took heed, and as newer, more robust designs replace the old designs, the percentage of leaker-free plants has been steadily increasing.

Westinghouse is one of the fuel vendors that has worked diligently to obtain leak-free fuel performance, primarily through the introduction of more robust fuel designs. As of December 2013, 147 plants worldwide were using Westinghouse fuel. Figure 1 shows the leak-free plant performance for reactors with Westinghouse-supplied fuel, indicating a steady increase in the percentage of leak-free plants as a result of the introduction of the robust designs. The figure also displays data from INPO, which includes U.S. plants fueled by other vendors for comparison purposes. The data illustrates that plants with Westinghouse fuel consistently operate with a higher percentage of leak-free cores compared to those with fuel provided by other vendors.

LEAK FREE PERFORMANCE OF REACTORS*



*With Westinghouse Electric Company Nuclear Fuel and Industry Wide Data From INPO (all fuel vendors)

DEVELOPMENT OF ROBUST FUEL DESIGNS

In order to achieve these results, the modern robust fuel was designed with criteria that addressed the specific challenges encountered by prior designs. Westinghouse strengthened the product development and design review processes through better test protocols based on field examinations, rigorous use of the problem identification and resolution process known as the Corrective Action Process (CAP) to identify root causes and corrective actions to prevent recurrence. Systematic use of Human Performance principles was also introduced in the design process. The design review process formality and rigor has also been increased, and multiple formal review steps during the development process are required, as are thorough documentation and independent review of engineering, and manufacturing analysis and testing.

Reliability in manufacturing has been strengthened by routinely applying failure modes and effects analysis (FMEA) to the manufacturing process steps, with focused attention on manufacturing steps closely tied to product parameters that determine fuel performance. To enable the manufacturing process improvements introduced from this process to be sustained, a subset of the product specifications and requirements has been defined as critical fuel reliability attributes (CFRA). These have been made an integral part of the Westinghouse CAP system so that items entered in the system are tagged if they are CFRA-related; if so, they get rapidly addressed by a standing fuel reliability improvement team. CFRA items are routinely tracked and trended to identify adverse trends and appropriate corrective actions. A global foreign material exclusion (FME) program also has been established across multiple manufacturing facilities to ensure foreign materials are not inadvertently introduced in the fuel product.

DESIGN CONSIDERATIONS FOR PWR FUEL

In PWRs, advanced designs have been developed for the Westinghouse 14x14, 15x15, 16x16 and 17x17 fuel rod lattices, the Combustion Engineering 16x16 lattice, and the VVER1000 lattice. The advanced BWR 10x10 lattice is the Optima3 design with the TripleWave+™ debris filter. In Japan, where the 9x9 lattice remains the standard array, NX1 is the advanced 10x10 design with 3D Screen debris filter developed by Nuclear Fuel Industries (NFI).

For PWR reactors, as previously stated, the most significant historic leaking mechanisms have been GTRF and debris fretting. Crud-induced corrosion failures and pellet cladding mechanical interaction due to missing pellet surface (MPS) have also occurred, but much less frequently. Other mechanisms, such as baffle jetting caused by degradation of reactor internals, have impacted fuel reliability at certain plants. The GTRF mechanism has been addressed in the new designs by both introducing modifications to the fuel rod supports and by adjusting the local flow conditions around the supports to suppress vibration mechanisms within the spacer grid and the overall fuel assembly.

To address debris fretting, a filter that prevents debris from entering the bundle serves as the first line of defense. However, additional measures are also used to prevent or mitigate debris entrapment by the grids along the bundle length. The design introduced for Westinghouse plants features a layered defense approach, consisting of a debris filter bottom nozzle, a protective grid, a longer bottom fuel rod end plug and a hardened cladding surface. The combination of these features has proven extremely effective, with no debris leakers in suitably equipped fuel since introduction in the early 2000s. The introduction of these features by Westinghouse was gradual, so the reduction in the number of leakers brought by each improvement was easily quantified. The 17RFA design, of which more than 7,200 assemblies have been delivered, includes all the anti-debris features identified above. In addition to the 17RFA design, other robust designs incorporated all the anti-debris remedies. More than 9,000 bundles of different designs have been operated with no debris-induced leakers.

Missing pellet surface area can occur during pellet manufacturing and pellet handling prior to loading into fuel assemblies. Each pellet is inspected with the objective of removing any pellets with missing surface in the range that poses a PCI risk. Detailed FMEAs, coupled with fuel performance modeling, were used to establish the maximum allowable missing surface. Improvements in the manufacturing process to eliminate pellet chipping during handling and enhanced missing pellet surface inspection were also implemented by Westinghouse. Power ramp rates during reactor start-up are analyzed and recommended to utilities. Since the implementation of these measures, no leaking fuel rods attributable to missing pellet surface interaction with the cladding have occurred.

Fuel performance issues that do not affect the integrity of the primary fission product barrier can also cause plant operational concerns. Some plants have experienced excessive fuel assembly distortion during irradiation, so much so that the timely introduction of the control elements for both PWR and BWR fuel has been impacted. For PWR bundles, distortion has been due to excessive fuel bundle growth. Structural material changes to low-growth alloys, such as ZIRLO® or Optimized ZIRLO™ have addressed the issue.

Excessive assembly distortion can also cause operational core-loading issues. The interaction between assemblies during normal fuel movements in the core when excessively distorted fuel assemblies are involved affects the integrity of the grids and increases the time required to load the core. Core-loading sequences designed specifically to facilitate loading mixed cores containing highly distorted fuel are able to be defined and have been successful in reloading cores without damaging the fuel.

DESIGN CONSIDERATIONS FOR BWR FUEL

In BWR reactors, the most significant leaking mechanisms have been debris fretting due to foreign material, PCI during power ramps and cladding crud and corrosion. Additional BWR reliability issues have also come from channel distortion. Over the past decade, the only fuel failure mechanism of any frequency for Westinghouse fuel has been debris fretting. Westinghouse first introduced a TripleWave™ debris filter in the late 2000s which significantly reduced BWR debris leakers. The SVEA-96 Optima3 fuel assembly, which has an enhanced spacer grid and further refined TripleWave+ debris filter design, was designed specifically to eliminate debris fretting by simultaneously optimizing both the debris filter catching efficacy and the spacer grid's ability to pass smaller debris. The spacer grid design forms a smooth, sleeve-type fit around the fuel rod, providing defense-in-depth against debris fretting. Testing has confirmed that if debris is small enough to pass through the TripleWave+ filter, it will not be trapped by the spacer grid. Optima3 has not experienced any leakers since its introduction.

For BWRs, control blade insertability concerns arise from channel bow and bulge, which at times necessitates bundle rechanneling before discharge. Plants experiencing excessive bundle distortion need to monitor the control rod drop times on a more frequent basis and take corrective measures when certain thresholds are reached. The Westinghouse Optima3 design uses a water cross reinforced channel with a low tin alloy to eliminate channel distortion throughout the normal lifetime of the bundle. Table 2 summarizes the performance of the Westinghouse PWR and BWR advanced designs.

TABLE 2 FUEL LEAKING RATE OF WESTINGHOUSE ELECTRIC COMPANY ADVANCED NUCLEAR FUEL DESIGNS

W-NSSS	Discharged Fuel rod Leaking Rate (in parts per million)	Number of Delivered Assemblies
14x14 (422 V)	0	1544
15x15 Upgrade	0	1911
17x17 Robust Fuel Assembly	0	7289
CE-NSSS		
16x16 Next Generation Fuel [1]	0	770
VVER		
VVER1000	0	216
BWR		
SVEA Optima3 TW+	0	354

(1) Currently one plant with this fuel type has had an increase in coolant activity

CONTINUOUS IMPROVEMENT- FUEL RELIABILITY IMPROVEMENT PROCESS

In order to maintain and continuously improve on fuel reliability demonstrated by the above-described robust fuel designs, Westinghouse has developed and implemented a fuel reliability improvement (FRI) process to drive continuous improvement in fuel hardware reliability.

The FRI process brings a continuous-improvement focus to fuel reliability by building on existing continuous improvement efforts, such as the CAP process, use of Six-Sigma tools and data analysis methodology, and Human Performance principles, while integrating the best practices of industry bodies such as INPO. The process works to ensure that operations feedback on fuel reliability from numerous sources, including PIE of discharged "healthy" fuel, RCAs, manufacturing data and the CFRA, are trended and critically analyzed to identify areas for improvement. Once improvement areas are identified, specific actions can be identified and taken. The range-of-action scope can vary, from a manufacturing process improvement implementable in weeks, to a fuel research and development activity that can take years of development and testing.

The portfolio of approved fuel reliability improvement projects is tracked through completion, reported through key performance indicators and monitored at least monthly. The governing fuel reliability improvement strategy, which drives the portfolio of projects, is revisited and updated at least yearly.

The global nature of the Westinghouse fuel business, with fuel manufacturing plants in the U.S., Europe and Japan, allows the company to leverage operating and manufacturing experience from across the globe, resulting in a rapid identification of potential impacts to fuel reliability and rapid implementation of preventive and/or corrective measures. Westinghouse has developed and deployed robust BWR and PWR fuel designs to address known leakage mechanisms and operational issues. As a result, the leak-free performance has improved dramatically and is currently greater than 95 percent. NPI