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Nuclear fuel performance: Trends, remedies and challenges

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A B S T R A C T

It is unacceptable to have nuclear power plants unavailable or power restricted due to fuel reliability issues. ‘Fuel reliability’ has a much broader definition than just maintaining mechanical integrity and being leaker free – fuel must fully meet the specifications, impose no adverse impacts on plant operation and safety, and maintain quantifiable margins within design and operational envelopes. The fuel performance trends over the last decade are discussed and the significant contributors to reduced reliability experienced with commercial PWR and BWR designs are identified and discussed including grid-to-rod fretting and debris fretting in PWR designs and accelerated corrosion, debris fretting and pellet-cladding interaction in BWR designs. In many of these cases, the impacts have included not only fuel failures but also plant operating restrictions, forced shutdowns, and/or enhanced licensing authority oversight. Design and operational remedies are noted. The more demanding operating regimes and the constant quest to improve fuel performance require enhancements to current designs and/or new design features. Fuel users must continue to and enhance interaction with fuel suppliers in such areas as oversight of supplier design functions, lead test assembly irradiation programs and quality assurance oversight and surveillance. With the implementation of new designs and/or features, such fuel user initiatives can help to minimize the potential for performance problems.

1. Introduction

Through direct contact with utilities, the Stoller Nuclear Fuel Division of NAC International has been compiling and trending the in-core performance of commercial PWR and BWR fuel designs fabricated by US and European fuel suppliers for about two decades. Using a two-year rolling evaluation period, supplier-specific failure rates are calculated by dividing the total number of failures by the total number of rods under irradiation, for those fuel cycles falling both fully and partially within that two-year window. The global failure rate is reported as the number of failed rods per 100 000 rods under irradiation. Although there is no ‘acceptable’ failure rate, a value less than 1 per 100 000 rods irradiated has traditionally characterized ‘best in class’ performance and can be achieved in the near-term. The failure statistics are based on utility-provided data on reload batch sizes, cycle operating dates, number of fuel failures, failure cause, etc.

It is recognized that there are a number of ways of reporting fuel failure rates. Using a two-year rolling period is one appropriate method of evaluating failure rates in plants operating with long cycles (i.e., 18- and 24-month cycles) with modern and advanced fuel designs without unduly carrying forward the performance of older designs that still reside in-core.

The failure causes for BWR and PWR fuel irradiated during the late-2003 to late-2005 period are provided below in Fig. 1. Failure causes are: ‘*DF*’ = debris fretting, ‘*GF*’ = grid-to-rod fretting, ‘*PCI/Duty*’ = duty-related failures including those attributed to classic pellet-cladding interaction (PCI) and PCI attributed to missing pellet surface and chips, ‘*Mfg*’ = manufacturing-related, ‘*AccCorr*’ = accelerated cladding corrosion, ‘*Unk*’ = failure examined but failure cause not identified, ‘*Nex*’ = not examined, and ‘*Est*’ = estimated failure(s) based on elevated coolant activities and their trends with time.

Fig. 1 shows that the primary failure causes continue to be grid-to-rod fretting in PWR designs (i.e., >50% of all failures) and debris fretting in BWR designs (i.e., >35% of all failures). In the ‘Est’ category, for PWRs, many of these failures are in-cores still operating with designs susceptible to grid-to-rod fretting – the majority of these are believed to be grid-to-rod fretting failures. For BWRs, many of these failures are believed to be a result of debris fretting.

Fig. 1 reflects a ‘snap shot’ of the latest period for which statistics are available. Trends in failure rates with time, remedies and their effectiveness are discussed below in more detail. Furthermore, perspectives on the best opportunity to further reduce failure rates and reliability issues are provided.

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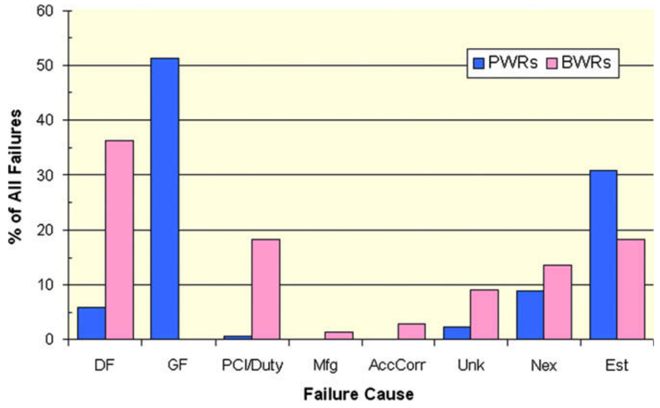

Fig. 1. Failure causes in PWR and BWR designs, two-year period ending late-2005.

2. Fuel reliability trends in PWR and BWR fuel

2.1. PWR reliability trends

The global trend in PWR fuel failure rates over the last 15-years is provided below as Fig. 2. Although failure rates have been evaluated on a supplier-specific basis, the data are combined as three trend lines, one for the maxima, one for the minima, and one for the average failure rates in each period through late-2005.

In the early 1990s, the primary failure mechanisms in PWR fuel designs were debris fretting and grid-to-rod fretting that affected multiple designs provided by multiple suppliers. The design remedies implemented to address debris fretting included more efficient filtering bottom nozzle designs along with the implementation, in some cases, of bottom grids that also acted as debris filters. At the same time, utilities significantly improved their debris exclusion programs and housekeeping practices to minimize the introduction of rogue materials into the primary coolant system. In regard to grid-to-rod fretting, the suppliers implemented a number of design remedies to (a) enhance the contact between the grid springs and fuel rod cladding, (b) balance the coolant flow within grids, and (c) change the vibration characteristics of fuel rods.

Overall, as evidenced by the trends in the minima and average failure rates, the remedies have proven effective – since 1999, the failure rate minima have ranged from 0.9 to ~1.6 per 100 000 rods irradiated in comparison to the maxima that approached 13.5 per 100 000 rods irradiated. Note that the trend of the maxima failure rates in the mid- to late-1990s were driven by failures primarily in one design and its variants. As those designs have been replaced by advanced designs incorporating larger grid-to-fuel rod contact areas, softer structures, and symmetric vane patterns, the total number of failures and the number of failures attributed to grid-to-rod fretting have significantly decreased. However, there is an upturn in the average and maxima failure trends in this latest period due to grid-to-rod fretting primarily as a result of fuel design transitioning effects. Note that the increased failure rates in 1996/1997 were due to a manufacturing-related issue affecting one particular design.

If the design remedies and the advanced designs under irradiation as LTAs can essentially eliminate grid-to-rod fretting, the *average* failure rate should decrease to slightly less than 2 per 100 000 rods, because a review of failure trends *without* grid-to-rod fretting included shows the average failure rate to be at about this level. Significant further improvement in reliability can only come from enhanced interaction between fuel suppliers and users.

As previously noted, fuel reliability is much more than a failure rate. The experience over the last decade clearly shows that if the fuel cannot meet its design and operational requirements, the impact on plant performance and resources can be as significant, if not more so, than fuel failures in-core. Such impacts include enhanced inspections, plant shutdowns, increased surveillances, and enhanced Licensing Authority oversight. Issues affecting reliability have included crud induced power shift (CIPS or axial offset anomaly) and incomplete rod insertion (IRI). Although these two particular issues were identified in the early to mid-1990s and design and operational remedies have proven effective, there are still some legacy impacts on current plant operation.

2.2. BWR reliability trends

The long-term global trends in the BWR failure rate are provided in Fig. 3. Similar to the PWR trends discussed above, the failure rates have been evaluated on a supplier-specific basis. The data, however, are shown in this figure as combined trend lines for the maxima, the minima, and the average failure rates in each period through late-2005.

In the last decade, the failure rates of BWR fuel designs have been about a factor of three times *lower* than those for PWR fuel – the maxima for BWR designs have ranged between about 2.7 and 4.5 per 100 000 rods irradiated and, for PWR designs, about 8.0 to 20.6 per 100 000 rods irradiated. However, the BWR failure rates do not show the generally improving trends observed for PWR failure rates.

A review of the failure statistics shows this to be due to isolated cases where a relatively large number of failures have occurred in

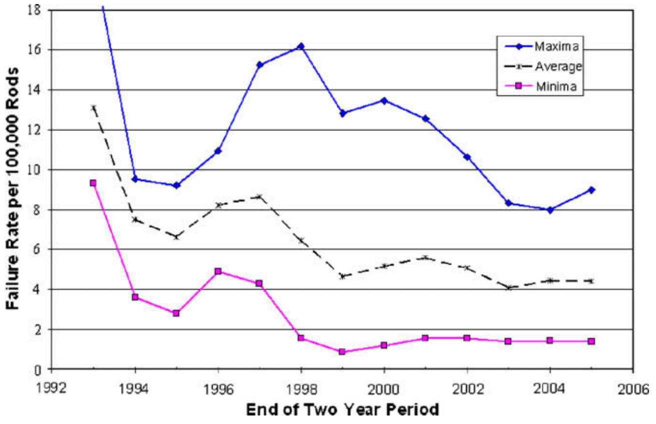

Fig. 2. Failure trends, PWR fuel designs.

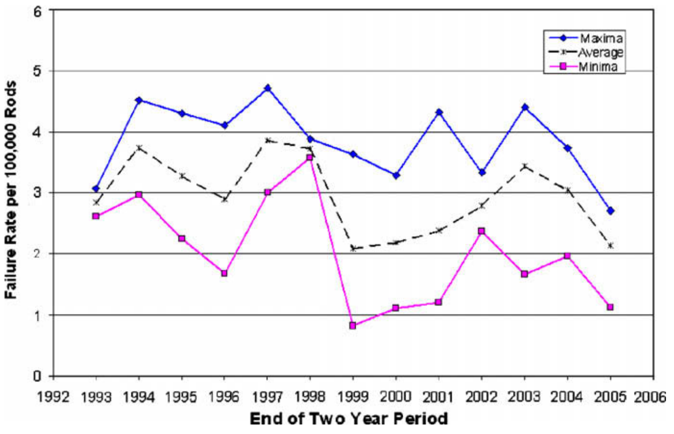

Fig. 3. Failure trends, BWR fuel designs.

relatively few plants. This is in contrast to the PWR experience where generic failure mechanisms have led to failures occurring in a number of different plants over a number of cycles of operation.

In regard to the BWR trends, examples of these isolated cases of failures include accelerated corrosion, non-classical PCI, and, to a certain extent, debris fretting. In the most recent case of accelerated corrosion failures, only three plants were affected yet the adverse impacts were substantial. For one of these plants, the impacts included ~63 failed assemblies, power derates, premature discharge of fuel, enhanced chemistry monitoring, modifications to cladding material chemistry, etc.

Although the majority of the accelerated corrosion failures occurred more that two-years ago and, consequently, are no longer included in the latest statistical evaluations, debris fretting (affecting primarily one supplier) and legacy non-classical PCI (affecting a second supplier) continue to be significant failure causes and are keeping the failure rate elevated at this time. Indeed, the latest statistics show that the number of confirmed debris fretting failures has increased by a factor 2–4 for the European and US fuel suppliers in spite of the implementation of debris-filtering tie plate features. If the factors contributing to the accelerated corrosion, debris fretting and non-classical PCI failures noted above were eliminated, the *average* BWR failure rate should fall to about 0.5 per 100000 rods.

The most significant reliability issue affecting BWR designs currently is channel bow. Although no fuel failures have resulted, bowing has adversely affected plant start-ups and has resulted in stuck blades. Utilities have spent significant resources to determine if their fuel designs are affected and, if confirmed, in implementing remedies (including channel replacement) and performing on-going blade operability tests.

3. The way forward

The statistics on fuel failure rates and recent reliability issues affecting the performance of nuclear fuel suggest that further reductions in failure rates and minimization of other issues adversely affecting fuel performance require enhanced cooperation between utilities, their fuel suppliers, and research organizations. Examples of actual and potential cooperative actions are noted below.

3.1. Comprehensive and thorough failed fuel root cause analyses

Poolside inspections of failed fuel provide the best means of identifying failure cause and contributory factors. Without detailed inspections, failure cause cannot be determined with certainty and the ability to use that information as feedback to the design process and/or operation will not occur.

Therefore, failed fuel should be non-destructively examined at the utility's plant site. The examinations should include, as a minimum, high magnification visuals and eddy current testing to help to characterize primary and secondary failure sites. Furthermore, in the case of debris fretting, retrieval of any remaining debris and its subsequent analysis is important in determining source and possibly means of deposition within the assembly.

Even without fuel failures, utilities have performed very detailed inspections during refueling outages on non-failed fuel across the full burnup range. The advantage of such a strategy is that the utility compiles an experience base of the 'expected' performance of their fuel in their particular plant operating under conditions that may be specific to their plant. Comparison of current vs. prior experience can identify unexpected and anomalous conditions possibly in advance of failure.

3.2. Hot cell examinations

For key contemporary failure mechanisms, hot cell examination of failed and non-failed fuel is warranted. For example, there appears to be an increasing trend in duty-related failures in BWR and PWR designs when operated under very aggressive, 18- and 24-month operating conditions in, for example, US plants. Hot cell examinations are instrumental in determining if the failure cause is non-classical PCI (i.e., due to missing pellet surface) or classic PCI (i.e., iodine assisted cracking). Results of the examinations can provide very direct feedback to the fabrication process. If non-classical PCI, the fuel supplier can re-evaluate current pellet integrity specifications, rod handling specifications, rod loading techniques, and so on. If classical PCI, the fuel supplier can re-evaluate uncertainties in-core design and surveillance methods, accuracy of modeling control element effects on rod local power, susceptibility of cladding materials to stress corrosion cracking, etc.

3.3. Supplier oversight

Further reductions in fuel failure rates will be accomplished, to a significant degree, through the development and implementation of advanced design features. Utilities should have comprehensive and thorough oversight/surveillance programs with their fuel suppliers not only in regard to the processes involved in developing a new feature but also in the fabrication of that feature and its integration into the fuel design.

3.3.1. Design review oversight

Taking an active role in the development of advanced features offers the utility the opportunity to independently review and question the bases for the design change, the scope of the testing performed and the results of those tests, as well as effects on the integrated performance of the fuel design. Furthermore, this allows the utility to evaluate the design feature against its own experience base.

3.3.2. Fabrication quality assurance (QA) oversight

It is critical that a utility has a robust oversight program of their fuel and component suppliers. With improved awareness of activities at their suppliers, utilities become more informed consumers of the fuel. A supplier oversight program should include the following important elements:

- Spend time in the supplier's fabrication facility to understand how fuel and components are manufactured. As part of this, be aware of the operational needs of the product. The relationship between fabrication and performance is recognized, but not always fully understood. In basic terms, what happens at the supplier's facility can have a dramatic impact on the performance of the fuel.
- The personnel responsible for this oversight need to understand the processes and the performance requirements in order to make efficient and valuable use of their limited time at the fuel suppliers.
- Sub-suppliers of material and components are as important, if not more so in some cases, than the fuel supplier. Performance characteristics directly related to material properties and component fabrication/processing are established at the sub-supplier's facility. Subsequent activities at the fuel supplier's facility may have no impact on these characteristics. Furthermore, key components such as grids/spacers and tie plates/nozzles are now, in some cases, supplied in finished configurations by sub-suppliers.

- Oversight should not be limited solely to fuel. Other key components such as control blades/rods, fuel channels, also have an effect on reliability and should, therefore, be part of the oversight process.

4. Conclusions

For PWR designs, significant improvement in failure statistics over the last decade are the result of the implementation of design features to first address debris fretting and then grid-to-rod fretting failure mechanisms. Over this period, the *average* failure rate has fallen from about 13 per 100 000 rods to 4 per 100 000 rods. However, the underlying trend is not improving. If grid-to-rod fretting failures in the design variants most significantly affected are excluded, since the late-1990s, the average failure rate has remained fairly constant at $\sim$2 per 100 000. Improvement will require enhanced cooperation between suppliers and their fuel users.

For BWR designs, although the failure rate has also exhibited a decreasing trend over the last decade from about 3 to 2 per 100 000 rods, much more variability is observed. This is due to isolated cases of relatively large numbers of failures affecting just a few designs and a few suppliers (e.g., accelerated corrosion, non-classical PCI, debris fretting). If these isolated cases are excluded from the statistics, the average BWR failure rate has asymptotically approached a value of about 0.5 per 100 000. Again, improvement can only come from enhanced cooperation between suppliers and their fuel users.

Enhanced cooperation will be important in three critical areas in order to further improve the reliability of BWR and PWR fuel designs:

- more comprehensive and thorough failed fuel root cause analyses to determine the cause and contributory factors of fuel failures,
- hot cell examination of failures attributed to key contemporary failure mechanisms (e.g., duty-related failures), and
- enhanced oversight of fuel suppliers relative to design activities and as part of the surveillance of fabrication activities.