# AXIOM-P

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# 1 Introduction

The main objectives of the AXIOM-P are:

- To discuss the mechanisms for development of primary and secondary defects in a fuel rod. The most common causes are pointed out and remedies for these causes are suggested.

- To provide a new and efficient model, AXIOM-P, for data analyses. This model can replace all current methods and models with respect to evaluation of routinely measured specific reactor water data for fuel defects. The model is presented and discussed. Recommendations how to use the model in the most efficient way are provided. The currently used methods for data analyses are also discussed.

The outline of the AXIOM-P report is as follows:

- Sections 2 and 3 provides an introduction to water cooled reactor designs (PWR/VVER, BWR and PHWR/CANDU), the respective coolant chemistries, the fuel assembly structures and materials.

- Sections 4 and 5 provides information about fuel reliability and how it can be optimised.

- Section 6 contains a discussion and summary of fuel reliability issues

- Section 7 provide information about the AXIOM-P code and its use.

- Appendix A and Appendix B gives information on noble gas content in gas free volumes and report used data, respectively.

- Appendix C and Appendix D covers the parameters impacting secondary degradation of failed PWR fuel and axial cracking mechanisms

# 2 Reactor characteristics

Currently, there are, [World Nuclear Association, 2015]:

- 66 PWRs operating in the United States,
  - 48 designed by Westinghouse (W),
  - 12 by Combustion Engineering (CE) and
  - 6 by Babcock and Wilcox (B&W).

  There are several differences between the designs, most notably B&W units having once-through steam generators (SGs) whereas the W and CE units have re-circulating U-tube SGs. In contrast to secondary chemistry issues, these design differences have little effect on primary chemistry strategies.

- In Western Europe there are currently 80 PWRs. The principle design of these stations is from W. They were built by W itself or by the two former licensees which were Framatome and Siemens.

- In Asia 76 PWRs are in operation.

Differences in design and operational experience between the PWRs in the different continents mentioned above are explained in LCC7 STR, [Riess et al., 2011].

In the very early days of PWR operation, heavy CRUD build-up on fuel cladding surfaces was caused by the transport of Corrosion Products (CPs) from the SGs into the reactor core, as for example in the first cycle of the Obrigheim NPP. As a result, activated CPs caused high radiation fields on out-of-core surfaces Figure 2-1 fuel performance was compromised and even coolant flow issues were observed in some plants.

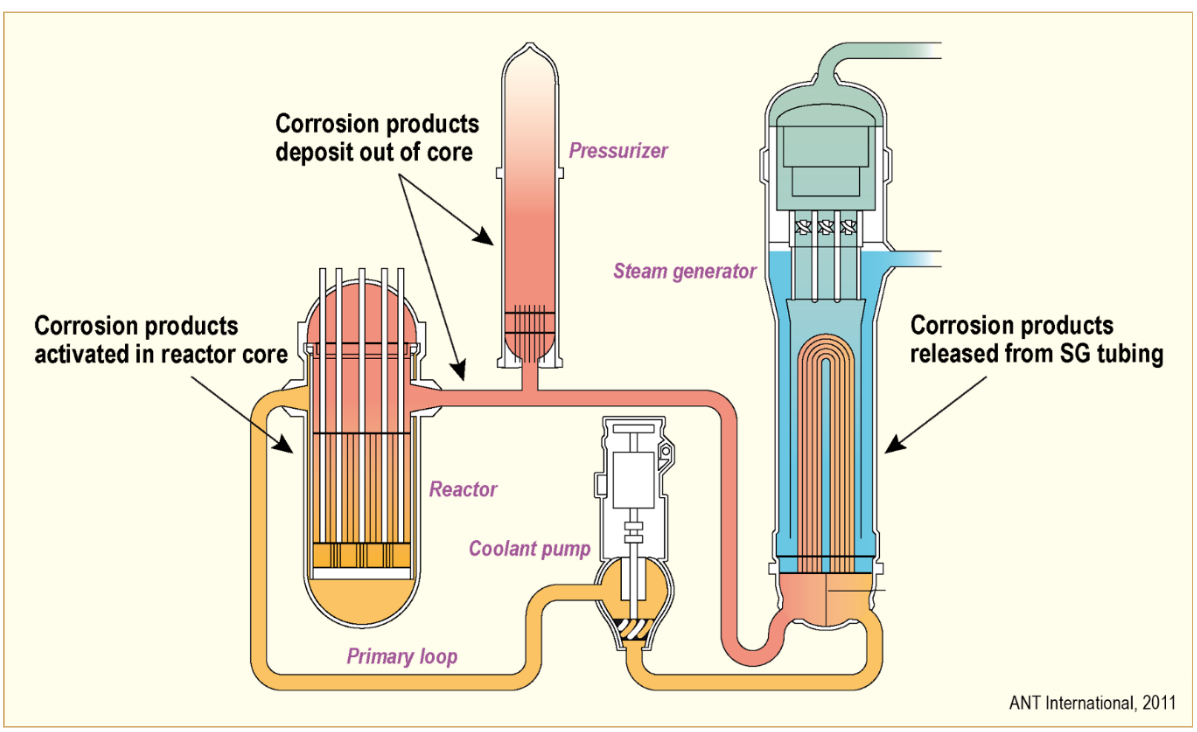


Figure 2-1: Transport and activation of CPs in PWR primary systems, after [Wood, 2008].

These problems related to CPs were initially mitigated by imposing a hydrogen overpressure on the primary system, to reduce the electrochemical corrosion potential, and raising the primary chemistry pH. Materials degradation in primary systems was then not a major concern, with most of the emphasis focused on secondary side corrosion issues in the SGs. Commercial PWR power plants use a steadily decreasing concentration of boric acid as a chemical shim throughout the fuel cycle, which results in the use of lithium hydroxide to control pH. Some 30 years ago, the concept of "coordinated boron and lithium" was developed, whereby the concentration of LiOH was gradually reduced in line with the boric acid reduction to maintain a constant pH. Furthermore, it was determined that heavy fuel CRUD build-up was avoided if a constant pH of at least 6.9 was maintained. This was possible with 12-month fuel cycles, but fuel cladding corrosion concerns limited the maximum LiOH concentration to 2.2 ppm. As a result, plants often started the fuel cycle with pH below 6.9, which resulted in radiation fields remaining relatively high. Although research and plant demonstrations showed that the 2.2 ppm limit was excessively conservative, the move to higher Li concentrations was initially slow. However, detailed fuel examinations from various plant demonstration programmes have indicated that Li can be raised to as high as 6 ppm without any fuel corrosion issues. In parallel optimizations of the fuel cladding material allow the operation at enhanced pH-values.

About 25 years ago, Pressurised Water Stress Corrosion Cracking (PWSCC) of Alloy 600 Steam Generator (SG) tubes were observed in a few plants, leading to studies on mitigating this effect. Following successful demonstration of zinc injection in BWRs, initial field tests at European and U.S. PWRs revealed, that radiation fields were reduced, and laboratory studies in U.S. indicating that PWSCC was reduced, these facts were eventually confirmed. As a result, zinc injection is now being implemented at an increasing rate, although concerns about fuel performance at high duty plants (plants with significant subcooled boiling) have not been completely resolved. Most recently, especially in the U.S. plants, build-up of boron-containing CRUD in areas of sub-cooled nucleate boiling leading to localized flux depression (Axial Offset Anomaly - AOA[1]) has encouraged the use of higher Li concentrations to minimize CP transport. However, in particular in German PWRs these problems were not experienced because of more iron-rich CRUD. Concerns about the potential adverse effects of zinc deposited in high-CRUD regions has resulted in several highly-rated plants applying in-situ Ultrasonic Fuel Cleaning (UFC) to remove CRUD from the fuel before implementing zinc injection.

The identification of PWSCC in reactor vessel penetrations in the last 15–20 years has encouraged the use of zinc injection, but has also focused attention on the effects of dissolved hydrogen, for which the recommended range has remained in 25–50 ml/kg for 30 years. It now appears that raising hydrogen will reduce PWSCC propagation rates, while lowering it may delay initiation of PWSCC. The interactions of materials, radiation fields and fuels in PWR primary chemistry and optimization issues covered in the Water Chemistry Guidelines, are depicted in Figure 2-2 .

[1] AOA, also called Crud Induced Power Shift (CIPS), is a phenomenon, which is caused by boron absorption in PWR fuel crud in the upper part of the core. The boron absorbed causes a reduction of neutron flux resulting in power reduction in the upper core region. In order to maintain overall power, the flux shifts downward in the core, resulting in uneven power distribution in the core. The following three conditions are required for the occurrence of AOA:

- SNB at the fuel clad surface,
- crud deposits in the boiling regions of the fuel rods, and
- boron absorption in these fuel crud deposits.

For more information, see e.g. Section 5.2.3.4 in LCC7 STR on PWR/VVER Primary Side Coolant Chemistry, [Riess et al, 2011].

# 3 PWR fuel design

## 3.1 Introduction

In PWRs there has been a trend to greater subdivision of fuel rods, e.g. from 15×15 to 17×17 fuel assemblies in PWRs of the Westinghouse design. However, since the control rods and control rod drives in PWRs are designed for a specific lattice configuration, they do not have the same flexibility with respect to changing fuel designs as BWRs. There is however, one exception namely DC Cook 1 which is switching to 17×17 by changing the reactor internals. Figure 3-1 shows the current PWR fuel rod arrays.

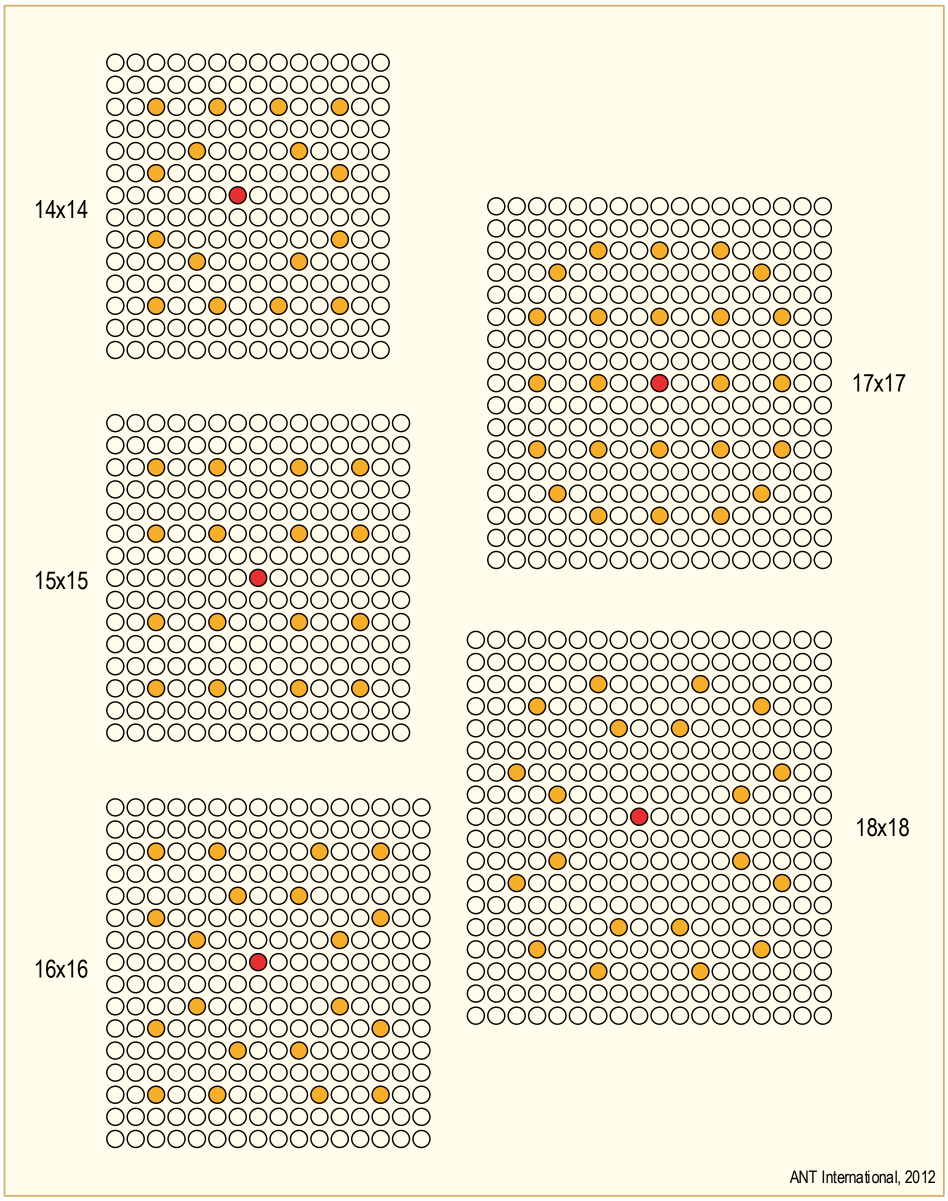


Figure 3-1: Layouts of different PWR fuel assembly arrays. Rods marked with yellow colour are guide tubes into which the control rod cluster is inserted. The position marked by a red filled circle is the instrument tube position.

In most PWRs, the assemblies are positioned in the core by bottom and top fittings, and the lateral clearances are restricted by the assembly-to-assembly contacts at the spacer-grid levels. PWR control rods consist of Rod Cluster Control Assemblies, RCCAs, the poison part of which moves into guide thimbles or tubes (GTs). These guide thimbles are an integral part of the assembly structure.

As an example of a PWR fuel design, the High Thermal Performance (HTP) design (former Siemens design) is shown in Figure 3-2 . The unique feature of HTP grid concept is that the fuel rods are supported in the grids along four pairs of continuous lines, providing a large grid-to-rod contact surface with coolant mixing being affected by curved internal flow channels. The HTP mid span mixing grid has no contact between the grid and the fuel rod. These grids are only used to improve thermal-hydraulic performance. The FUELGUARD bottom nozzle design Figure 3-3 , was originally designed for HTP fuel but can be used for all designs as a means for preventing debris from entering a fuel assembly with the reactor coolant.

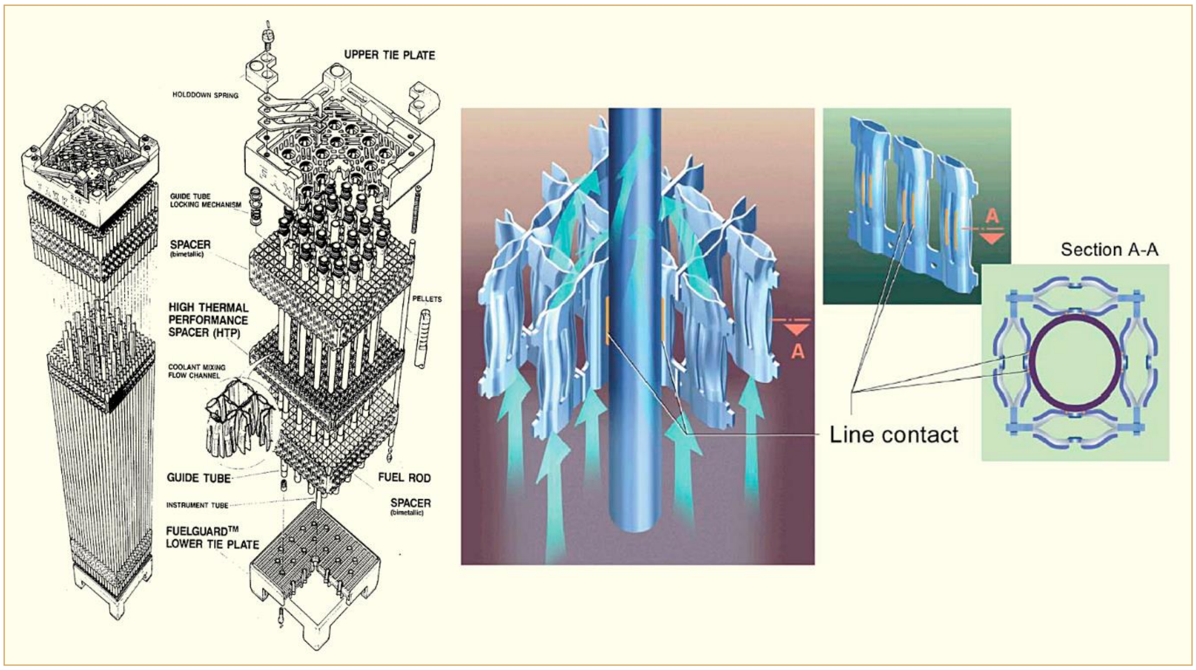


Figure 3-2: AREVA NP PWR HTP 17×17- HTP spacer grid design [Baleon et al, 2001].

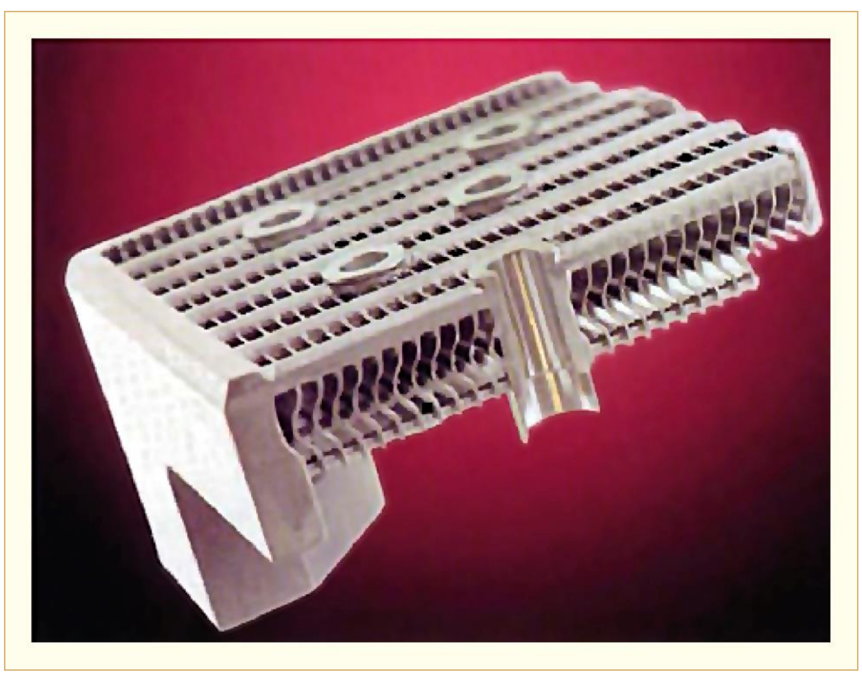

Figure 3-3: FUELGUARD bottom nozzle, provided by the courtesy of AREVA NP.

# 4 Fuel Reliability

## 4.1 Introduction

Although the performance of water reactor fuel has improved greatly relative to early experience, social, regulatory and operational incentives exist to both maintain the gains that have been achieved and to make further improvements in fuel reliability. The primary objectives in these areas are to increase fuel reliability by:

- Reducing the primary fuel failure frequency and minimize the consequences of fuel failures when they occur and
- Minimizing operational effects due to factors such as fuel assembly and channel bowing, that can affect thermal margins (LOCA, DNB, Dryout) and core control capabilities (control rod insertion).

In this report, reliability is considered in terms of:

- The ability of the cladding and end plugs comprising a fuel rod to isolate the fuel material and fission products from the primary coolant and to maintain the fissile material in the intended configuration. Failure is defined as the loss of the barrier between the rod interior and coolant such that fission products, fuel material or both are released to the primary coolant.
- Assuring that the fuel system[10] dimensions remain within operational tolerances, and that functional capabilities are not reduced below those assumed in the safety analysis.

Poor fuel reliability can have adverse effects on:

- Reduced thermal and safety margins,
- Power generation,
- Outage time,
- Chemistry and radiation monitoring costs,
- Personnel exposure,
- Handling, transportation, storage and reprocessing.

Maintaining and improving fuel reliability requires an understanding of the behaviour of fuel and materials as related to in-reactor conditions and the mechanisms that have been observed to cause fuel failures. A key factor in improving fuel reliability is the identification of the cause or causes of failure. Such information, in turn, requires the examination and analysis of irradiated fuel at reactor sites (poolside examinations), in hot cells and in related laboratories. Thus, to make progress toward ultra-high reliability fuel and to reduce the potential for post-failure degradation, it is imperative to examine both failed and non-failed (reference) fuel. The most cost efficient way to carry out these examinations is to begin with a good understanding of the known mechanisms of failure and degradation and of the principal methods for examining irradiated fuel. With such an understanding, fuel investigation and development programs can be focused on the likely causes of failure or degradation, while unnecessary

[10] Fuel system consists of assemblies of fuel rods including fuel pellets, insulator pellets, springs, tubular cladding, end closures, hydrogen getters, and fill gas; burnable poison rods including components similar to those in fuel rods; holddown spring, connections, spacer grids and springs; end plates; channel boxes; and reactivity control elements that extend from the coupling interface of the control rod drive mechanism in the core.

costly and time consuming work can be minimized. One of the objectives of this Report is to provide such an understanding.

Issues related to fuel reliability are reviewed in this report.

## 4.2 Current Status of fuel reliability

The most recent comprehensive survey of fuel reliability was published by the [IAEA, 2010] and subsequently evaluated in an IAEA paper by [Inozemtsev & Onufriev, 2013]. Experience is also being compiled by EPRI from U.S. and some European and Asian plants in its fuel reliability database (FRED). Publically available information through late 2015 is reviewed in the ZIRAT20 Special Topical Report titled "Fuel Reliability", [Rudling & Patterson, 2015]. A limited amount of information became available after 2015 and was reviewed in the ZIRAT21 and ZIRAT22 Annual Reports. More recent information is reviewed in this section.

Work in the area of fuel performance and reliability since the time of the IAEA survey has focused to a large extent on accident tolerant fuel (ATF) and the response of fuel to off-normal and accident conditions. These topics are reviewed in subsequent sections of the Annual Report. As background for reviews of these topics and of fuel reliability, design conditions relevant to fuel and fuel assembly materials are discussed briefly in this section.

The classification of design conditions typically applied to water reactor fuel is summarized in Table 4-1. The design conditions in this table are based on the expected frequency of occurrence and the potential effects of the respective events on NPP safety. The criteria for and designation of these design conditions vary slightly among regulatory authorities and have evolved with experience over the past 10 years, particularly after the earthquake and tsunami that affected the Fukushima Daiichi nuclear power plants in 2011. The classifications generally comprise normal operation (NO), anticipated operational occurrences (AOOs), design basis accidents (DBAs) and some combination of beyond design basis accidents (BDBAs), severe accidents (SAs) and design extension conditions (DECs). In all countries, the license applicant is expected to identify the specific list of events and conditions to be analyzed [NEA, 2014]. Note, however, that prescriptive regulations such as those of the NRC also specify events and conditions that must analyzed.

For reference, the design conditions of the NRC (10 CFR 50) and the American National Standards Institute ANSI/ANS-57.5 are reflected in the variations developed by many regulatory authorities. The ANSI/ANS 57.5 standard was initially approved in 1981, revised in 1996, reaffirmed in 2006 but withdrawn in 2016. The withdrawal is believed to reflect ongoing work to address events represented by what has been identified as Beyond Design Basis Accidents, Severe Accidents or Design Extension Conditions. However, the underlying design condition events of ANSI/ANS-57.5 agree with those of 10 CFR 50 and the IAEA and remain in common usage. The actual ANS standard is, however, unofficial with respect to most regulations.

The frequencies of the design event conditions in Table 4-1 are approximate and are provided for perspective. For example, the bounds for AOOs according to 10 CFR 50 range from once per reactor year to once per reactor life. These limits corresponding to a frequency of occurrence less than approximately 0.02 events per reactor year, but are shown as 1 – 0.01 per reactor year in Table 4-1. The frequency ranges in Table 4-1 come from [IAEA, 2016a] and [NEA, 2014].

# 5 Fuel reliability improvement

## 5.1 Introduction

For political and economical reasons, there are objectives to reduce the primary fuel failure frequency as much as possible and to minimize the consequences of fuel failures when they occur.

Fuel failures can have adverse impact on:

- Power generation.
- Outage time.
- Chemistry and radiation monitoring costs.
- Personnel exposure.
- Handling, transportation and storage or reprocessing.

The cost per failure was recently estimated by [Lemons, 2008] to range from $1 000 000 to more than $20 000 000 depending upon the type of reactor, the need for power suppression or a mid-cycle outage, reduced cycle length, the cost of replacement energy and the impact of the leaking fuel on subsequent core designs, operation and post-irradiation handling. The loss of generating capacity is a significant component in the cost of fuel failure. Generating capacity can be lost in power suppression tests to locate leaking fuel assemblies, in power reductions to minimize the risk of degradation of a leaking fuel rod, in mid-cycle outages to remove leaking assemblies and in operating cycles that are cut short by control blade insertions or unacceptably high coolant or off-gas activity. Generating capacity can also be adversely affected in subsequent reactor cycles by non-optimal core loading or operating compromises as a result of action taken to manage a leaking *FA*.

While *PWR*s are capable of operating with leaking fuel rods without adversely affecting safety, degradation of the affected rods after failure (secondary damage or degradation) can increase the release rate of gaseous, soluble and insoluble fission products. In the degradation process, enlargement of the leakage path and exposure of fuel pellets to flowing coolant leads to oxidation and mass transfer (washout) of fuel particles from the damaged rod to the primary coolant system. These dispersed fuel particles, generally called “tramp uranium”, can stick to the surfaces of fuel rods and other primary system components. The particles that deposit in the core continue to fission and release radionuclides directly to the coolant. Depending on the extent of degradation and the amount of fuel washout, long-term activity increases due to tramp uranium can be significantly larger than the steady-state increase from a leaking rod prior to degradation. The increase due to washout continues after the degraded rod has been removed from the core. Activity due to tramp uranium decreases in rough proportion with the fraction of the affected fuel assemblies that are discharged each reactor cycle; e.g., 6 – 10 years to return to pre-degradation activity levels. So, another significant component of the failure cost arises from the long term increase in exposure levels and action necessary to mitigate their effects.

The Executive Board of the Institute of Nuclear Power Operations (*INPO*) set the goal of eliminating fuel failures in all U.S. plants by 2010 [*INPO*, 2007]. The Chief Nuclear Officers of U.S. utilities have since pledged their support. While the feasibility of “zero leakers” as opposed to “as low as reasonably achievable” remains to be established, an integrated approach by suppliers, operators and regulators to achieving ultra-high reliability fuel is expected to benefit operational, cost and exposure issues. A key factor in such an approach is the examination and analysis of irradiated fuel at reactor sites, in hot cells and in related laboratories. Thus, to make progress toward ultra-high reliability fuel and to reduce the potential for post-failure degradation, it is imperative to examine failed and non-failed fuel. The most cost efficient way to carry out these examinations is to begin with a good understanding of the known mechanisms of failure and degradation and of the principal methods for examining irradiated fuel. With such an understanding, fuel investigation and development programs can be focused on the likely causes of failure or degradation, while unnecessary costly and time consuming work can be minimized. One of the objectives of this Handbook is to provide such an understanding.

For reference, a brief summary of fuel failures mechanisms is given in Table 4-3. Failures due to the first two causes, manufacturing defects and cladding collapse, are relatively infrequent. The exception is pellets with chips or missing pellet surface. Such pellets have been involved in recent *PCI* failures and are the object of ongoing manufacturing development. Another potential exception is primary hydriding. Failures due to primary hydriding were effectively eliminated by the introduction of fuel pellets with little or no open porosity and by the exclusion of moisture and other hydrogen-bearing material from the inside of fuel rods during the final assembly process. However, the underlying risk still exists and could lead to fuel failures in the event of an undetected excursion in moisture contamination. Fuel failures due to excessive cladding corrosion are also relatively infrequent. Corrosion failures typically result from a common cause or a set of causal factors and can affect a large number of rods in a given reload or core. The rate of *PCI* failures was greatly reduced by introduction of operating guidelines (on ramp rates) but appears to be increasing with more demanding core loadings and operating cycles; i.e., longer cycles, more rods at the upper end of the design range, larger power ramps to high powers after longer times at low power. As noted in Table 4-3, some of the recent duty-related failures have also involved pellets with missing cylindrical surface. Cladding perforation due to fretting remains as the leading recurrent failure mechanism. Fretting due to the trapping of foreign material next to fuel rods is a source of failures in *PWR*s. The frequency of failures due to debris fretting varies among reactors, ranging from none in some plants to multiple rods in multiple cycles in other plants. The frequency of such failures is decreasing, however, due to debris filters in fuel bundles, strainers in feedwater lines and debris exclusion practices by the fuel suppliers and reactor operators. Fretting due to fuel rod vibration relative to spacer grids is a problem unique to some *PWR* fuel designs and plants.

Key to improve fuel reliability is to determine the fuel failure cause even for discharged fuel. Only a complete understanding of the failure root causes may improve fuel reliability. The various poolside and hot cell examinations to determine the fuel failure root causes are provide in [Mahmood et al., 2014].

Reasons for fuel failure are as outlined below and described in Table 5-1:

- Poor design (including operation outside the experience base of the design) – this failure mode can be eliminated by a fuel design review. Effective Fuel Design Reviews are treated in the ANT International Fuel Design Review Handbook, [Strasser et al., 2010b].
- Poor manufacturing process – this failure mode can be eliminated by good fuel fabrication practice. See ANT International Fuel Fabrication Handbook to minimize fabrication related defects [Strasser et al., 2014].
- Changes of coolant chemistry and/or duty outside the regime in which the fuel has been qualified for – this can be eliminated by
  - Healthy fuel examinations (HFE) to get early warning of an emerging fuel performance issue
  - Following the trends in the industry of fuel issues in other reactors related to new designs, materials or fuel failures due to fabrication/design flaws. Also the knowledge of fuel failure mechanisms impacting the fuel failure process may help to eliminate the problems.

# 6 Discussion and summary

The reliability of fuel in power-generating water reactors has improved and is now high relative to earlier experience. Fuel rod failure rates are slightly different among reactor types and countries. The latest tabulation by the IAEA shows, however, the average number of leaking fuel rods per discharged assembly is about 53 fpm for PWRs, [Inozemtsev & Onufriev, 2013]. This failure rate is for the 2004–2010 reporting interval and are similar to those of the previous 5-year interval.

Fuel rod reliability is affected by the performance of integral fuel assemblies as well as individual fuel rods. That is, the leading cause of failures in PWR fuel is grid-to-rod fretting, which is responsible for ~40% of the fuel failures. Debris fretting, which differs from GTRF, is observed in all types of fuel assemblies; e.g., ~13% of PWR failures. Although greatly reduced as a mechanism of recurrent failures, PCI/SCC accounts for ~3% of PWR failures. Fuel fabrication issues also affect all types of fuel, with ~11% of PWR failures due to manufacturing issues. The remaining 30–40% of the fuel failures are due to unknown or indeterminate causes; i.e., the failed fuel has not been inspected or the cause cannot be determined from the inspections that have been performed.

Grid-to-rod fretting issues are being addressed by changes in the designs of lower nozzles and grids. Nozzle improvements focus primarily on reducing the turbulence and non-uniformity of coolant flows in the lower elevations of a fuel assembly. Grid improvements include larger bearing areas between the fuel cladding and the structural supports in the grids; i.e., springs and dimples. Some of the design changes also involve the use of relaxation-resistant, Ni-based spring materials. Although these changes are similar to those implemented in earlier designs, the likelihood of actually reducing the GTRF failure rates appears to be increasing because of ongoing improvements of capabilities for modeling fluid-structure interactions and the incorporation of modeling and test results into PWR fuel assembly designs.

Efforts to reduce the rate fuel failure due to debris fretting involve both the fuel suppliers and operating utilities. Debris exclusion practices have been established in manufacturing, transportation, storage and reactor facilities. Debris removal programs have been implemented in plants with debris in their primary coolant systems. Debris strainers have also been installed to reduce the amount of debris that is transported into the core by the primary coolant. More importantly, lower nozzles and tie plates have been developed to exclude or trap the small debris (metal turnings, chips, wires) observed to cause fretting of fuel cladding. Spacer grids are being redesigned to capture debris at elevations where flow-induced vibrations are low (entrance to a fuel assembly) and minimize the capture probability at elevations where vibrations are high (upper half of a fuel assembly).

Failures due to the PCI/SCC process have been observed in PWRs. This failure mechanism was essentially eliminated by operation restrictions on ramp rates. The current PWR trend to load follow due to that the power needs to be adjusted (with control rods) to the very irregular electricity production of renewables decreases the margins towards PCI. Also, the presence of missing pellet surface or pellet chips in the pellet-cladding gap increases cladding stress and has been observed to cause PCI failures under operating conditions where none should have occurred. Although all fuel suppliers are working to eliminate missing surface and pellet chips, the brittle nature of sintered $UO_2$ hinders these efforts and increase the importance of quality control and audit programs.

Failures due to manufacturing issues are sporadic but recurring. Issues that contribute to fuel failures such as defects in end plug-to-cladding welds or grid damage during assembly or handling appear result more from upset conditions that from systematic deficiencies. Having made that observation, however, the adoption of resistance welding is an example where design and processes changes led to a fundamental increase in the capability and margins to potentially damaging weld defect. Modifications to grid designs to reduce the likelihood of spring damage during assembly and band damage during handling are other examples where capability improvements should reduce the incidence of upsets. The sporadic and recurring nature of fabrication issues reinforce the need for manufacturing processes with large capabilities with respect to the limits on characteristics critical to fuel reliability and for quality control and audit programs to assure these capabilities are not compromised.

Fuel failures due to unknown and indeterminate causes pose a problem relative to the quest for ultra-high reliability. This category corresponds to fuel rod failures rates of 1–15 fpm. Although probability alone argues some of these failures are due to the mechanisms noted above, diligence is needed in the form of post-irradiation poolside and hot cell examinations to assure other failure mechanisms are not affecting fuel reliability.

Fuel assembly issues can also affect performance independent of fuel rod failures. Issues of significance include instances of control rod interference due to assembly distortion, grid damage during handling (loading and unloading of PWR fuel) and axial offset anomalies (PWR fuel). The distortion of PWR fuel assemblies results primarily from the effects of axial hold-down forces on guide tube creep and from the effects of gradients in fast neutron fluence on differential growth among the guide tubes in an assembly. Creep and growth issues are being addressed through the use of changes in guide tube materials and their heat treatment; e.g., the use of RXA Zry-4 and the code of Zr-Nb or Zr-Nb-Sn-Fe alloys for guide tubes. The design of guide tubes has been changed to increase their resistance to bending, while the design of hold down springs has been changed to reduce the axial force and bending moment applied to a fuel assembly. Reload design (core management) practices are also being used to minimize the difference in fluence and irradiation growth among guide tubes within each fuel assembly.