A Review of BWR Fuel Performance under Modern Water Chemistry Conditions

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ABSTRACT

The Boiling Water Reactor (BWR) was originally designed to operate with high purity water of almost theoretical conductivity as the reactor coolant. However, during plant operation, the reactor water accumulates impurities due to the ingress of soluble and insoluble metallic species through the feedwater system. Some of the common impurities introduced into the reactor water through the feedwater system include iron, copper and zinc, the latter two species coming from the brass condenser tubing. These impurities and other minor alloying elements arising from stainless steel and nickel alloy components accumulate on fuel cladding surfaces as crud due to boiling in the core. During the early 80’s several BWRs suffered crud induced localized corrosion (CILC) due to deposition of copper and other soluble impurities on Zircaloy-2 fuel cladding surfaces. The CILC related fuel failures were eliminated by simultaneous improvement of the cladding material and the replacement of brass condenser tubing with stainless steel or titanium alloys.

BWR water has also undergone many chemistry evolutions over the past few decades as a result of the need to control radiation fields and stress corrosion cracking of reactor internals. Some of the demanding chemistry changes include hydrogen addition, zinc addition, iron addition and noble metal chemical addition to many of the modern day operating BWRs. These demanding chemistry evolutions have challenged the performance of fuel cladding material in the recent years.

This paper will review and summarize the BWR fuel cladding performance under these demanding and improved modern water chemistry conditions. The paper will also provide a brief summary of the results of hot cell post-irradiation examination, results of crud composition evaluation, crud spallation and some fuel failure observations.

Key Words: Boiling Water Reactor, Fuel Performance, Hydrogen Addition, Zinc Addition, Noble Metal Chemical Addition
Introduction

The Boiling Water Reactor (BWR) was originally designed to operate with high purity water of almost theoretical conductivity as the reactor coolant. However, during plant operation, the reactor water accumulates impurities due to the ingress of soluble and insoluble metallic species as well as non-metallic species through the feedwater system. Some of the common metallic impurities introduced into the reactor water through the feedwater system include iron, copper and zinc, the latter two species coming from the brass condenser tubing. These impurities and other minor alloying elements arising from stainless steel and nickel alloy components accumulate on fuel cladding surfaces as crud due to boiling in the core. During the early 80’s several BWRs suffered crud induced localized corrosion (CILC) due to deposition of copper and other soluble impurities on Zircaloy-2 fuel cladding surfaces. The CILC related fuel failures were eliminated by simultaneous improvement of the cladding material and the replacement of brass condenser tubing with stainless steel or titanium alloys.

Among the non-metallic impurities, the most common are chloride and sulfate ions due to potential condenser tube leaks or due to the ingress of resin fines containing sulfates respectively. While chloride ingress is not common, sulfate ingress and hence increased reactor water conductivity has not been uncommon in the early to mid 80’s as shown in Figure 1 [1]. It is quite possible that during this period of time some incipient cracks may have been initiated in the reactor internal materials that have undergone slow growth in subsequent years. However, Figure 1 also shows that water chemistry improved rapidly over the next decade to an extent that many BWR plants in the US operated with water chemistry close to theoretical conductivity except when plants employed additives such as zinc for dose rate control, or when reactor water chemistry changes from reducing to oxidizing conditions that could release chromates and sulfates.

Over the past few decades, BWR water has undergone many chemistry evolutions as a result of the need to control radiation fields and stress corrosion cracking of reactor internals. Some of the demanding chemistry changes include hydrogen addition, zinc addition, iron addition and noble metal chemical addition to many of the modern day operating BWRs. These progressive chemistry evolutions, described below, have challenged the performance of fuel cladding material in the recent years.

1. Hydrogen Water Chemistry (HWC)

Hydrogen water chemistry (HWC) is the addition of hydrogen to the feedwater of a BWR [2] to control the electrochemical corrosion potential (ECP) of reactor internal components to the HWC specification value of \(< -0.230 \text{ mV(SHE)} \). When this is accomplished for a reactor internal component, the initiation and growth of intergranular stress corrosion cracking (IGSCC) is mitigated as has been shown by many laboratory tests [3,4]. Although HWC is effective in mitigation IGSCC of reactor internal materials, it also has two side effects, 1) $^{16}\text{N}$ increase in the main steam causing increased operating dose rates, and 2) increased drywell or shutdown dose rates due to the transport and deposition of $^{60}\text{Co}$ on out of core surfaces.

2. Depleted Zinc Oxide (DZO) Addition

The drywell or shutdown dose rate management is an issue that the plants had to deal with during their early years of operation. This is largely due to the use of cobalt containing materials such as stellite in some reactor internal components like control rod blade pins and rollers. The cobalt that gets released from these surfaces due to corrosion gets activated in
the core to $^{60}\text{Co}$ that has high gamma energy and a long half life. The radioactive $^{60}\text{Co}$ deposits on out of core piping surfaces such as the recirculation piping resulting in increased drywell dose rates. During the early years of operation, the plants have managed to control the drywell dose rates by decontaminating the piping surfaces frequently. However, this provides only temporary relief since the dose rates rapidly increase back to the original levels at every refueling outage since fresh $^{60}\text{Co}$ incorporates on the piping surfaces as the piping gets oxidized during plant operation. In the later years, this situation was better managed by the addition of depleted zinc oxide (DZO) into the feedwater that helped in reducing $^{60}\text{Co}$ incorporation on piping surfaces due to the greater thermodynamic stability of zinc ferrite and zinc chromite as opposed to their cobalt counterparts [5].

3. Iron Injection to Control Piping Dose Rates

There are low crud plants with typical fuel crud loading of the order of a few hundred grams of crud per fuel element. The iron concentrations in both feedwater and reactor water can be very low resulting in a high feedwater Ni/Fe ratio of the order of ~ 0.5 [1]. This ratio is much higher than 0.16 to 0.2 recommended by Nagao et al. [6] for maximum reduction of the activity in the reactor water and the radiation dose on piping surfaces. The hypothesis here is that Ni and Fe$_2$O$_3$ react to form Ni-Ferrite on hot fuel clad surfaces. Since the chemical properties of Ni and Co are similar, Co gets incorporated into the ferrite matrix, thus effectively removing Co from the reactor water and hence cannot contribute to the recirculation piping dose rate increases [6]. On the other hand, if there is a very low level of Fe, the Ni/Fe ratio remains high and the formation of stable Ni-Ferrite phase is inhibited and therefore, more Co remains in the reactor water contributing to dose rate increases. This was observed at a number of plants before the implementation of HWC [1].

4. Noble Metal Chemical Addition (NMCA)

NMCA is a process where low concentrations (10 to 100 ppb) of soluble noble metal compounds of Pt and Rh are injected into the reactor water through the recirculation piping system. The application is performed during hot standby at a temperature in the range of 125 to 143°C, where the temperature is maintained at the desired value using shutdown cooling system or under steaming mode conditions. The process deposits fine noble metal particles of nano-meter size on all wetted surfaces rendering them catalytic. Thus, when excess hydrogen is added into the reactor feedwater, component surfaces have basically zero oxygen on the surfaces because of the rapid catalytic recombination of hydrogen and oxidants (oxygen and hydrogen peroxide). This process lowers the ECP of components to the desired HWC specification potential of < -230 mV(SHE) at low feedwater hydrogen concentrations, thereby largely eliminating one of the side effects of HWC, i.e. operating dose rate increases due to $^{16}\text{N}$. Details of typical NMCA applications are described elsewhere [7,8]. An example of an effective ECP reduction following NMCA is shown in Figure 2.

5. On-Line NMCA (OLNC)

The On-Line NMCA application technology was developed to address two primary issues, the first being to mitigate against crack flanking and the second being to save outage time that cost Utilities implementing conventional NMCA about 60 hours of critical path time. OLNC can be applied while the plant is in full power operation by injecting noble metal (ppt level soluble Pt chemical) into the feedwater system, thus eliminating the need for critical path time for the application. Moreover, since the application is performed on-line, it provides the
convenience of a reapplication if a hydrogen interruption occurs, thus mitigating any impacts due to crack flanking. The details of OLNC process and crack flanking appear elsewhere [9-12]. The OLNC process deposits finer nano-particles (2 to 12 nm) of Pt on surfaces, compared to NMCA, that make them super-catalytic to the H2/O2 recombination reaction resulting in very efficient ECP reduction as illustrated in Figure 3.

This paper will review and summarize the BWR fuel cladding performance under these demanding and improved modern water chemistry conditions. The paper will also provide a brief summary of the results of hot cell post-irradiation examination, results of crud composition evaluation, zirconium oxide and crud thickness variations, crud spallation and some fuel failure observations.

**BWR Fuel Performance Evaluations**

Typical BWR fuel performance evaluations include the following:

i) Pool-side visual examination of fuel cladding and photography

ii) Fuel rod oxide and crud thickness measurements using eddy current lift-off technique

iii) Fuel crud loading and analyses in the hot cells

iv) Fuel rod oxide and crud thickness measurements by post-irradiation examination (PIE) in the hot cell using metallography, if necessary

v) Fuel cladding hydrogen analysis in the hot cell

vi) Zirconium hydride distribution in the cladding when necessary

The following sections describe the BWR fuel performance evaluations completed following the progressively improved water chemistry changes.

**Fuel Performance Experience Before and After HWC**

The impact of HWC on fuel performance was first evaluated at Dresden-2 BWR in 1983 with a feedwater hydrogen concentration in the range 1.0 to 1.4 ppm [13]. Four fuel bundles containing both heat treated and non-heat treated cladding were examined for fuel performance at each of the subsequent outages after four 18 months cycles with a maximum burn up of 38 GWd/MT. The results showed that HWC had no adverse impact on fuel performance. The fuel rod deposits were hematite, similar to the pre-HWC experiences. Metallographic examination of the heat treated tubing showed an average oxide thickness of 10 µm with a maximum at 20 µm. Fuel cladding hydrogen content of the four cycle rods had a peak value of 50 ppm, similar to the non-HWC plants.

Figure 4 shows the results of the pool side rod oxide thickness measurements made using the eddy current lift-off technique that measures the total of adherent crud and oxide thickness after corrections are made for the ferromagnetic effect of the crud. The plot shows the rod average lift-off as a function of exposure for modern fuel cladding with and without HWC. Clearly, the data after HWC are right within the lift off experience base before HWC was implemented at Dresden 2 reactor, again showing no impact of HWC on fuel cladding performance.

Typically, approximately 70 to 90% of the feedwater iron oxide deposits on the fuel surfaces. For both filter demineralizer condensate clean up plants and plants with deep bed clean up systems, the amount of crud on fuel deposits was within the experience base of non-HWC
plants [14]. Therefore, hydrogen addition did not alter the fuel rod deposit amount either, as will be shown in later figures.

Thus, the Dresden 2 fuel surveillance program showed no fuel performance issues associated with hydrogen water chemistry [13].

**Fuel Performance Experience Following DZO Implementation**

Zinc addition to BWRs help to reduce personnel exposure by limiting the transport of $^{60}$Co from fuel rod deposits to out-of-vessel components [15]. This effect was discovered based on the piping dose rate behavior of “natural zinc” plants whose zinc source is the corrosion of the brass condenser tubes. When zinc is present in the reactor water, it facilitates the formation of zinc ferrite spinel on fuel rod deposits instead of the $\alpha$-Fe$_2$O$_3$ (hematite). The zinc atoms occupy lattice locations that would otherwise have been occupied by cobalt because of the greater thermodynamic stabilities of zinc ferrite and zinc chromite as opposed to the stability of cobalt ferrite [5]. Since natural zinc contains > 50% $^{64}$Zn that gets activated to the undesirable $^{65}$Zn isotope, the preferred approach is to use depleted ZnO that contains < 1% $^{64}$Zn. Currently, all of the US BWRs and more than ten non-US BWRs are injecting DZO into the feedwater for radiation field and personnel exposure reduction.

Figure 5 compares the eddy current lift-off measurements following zinc addition with the non-Zn plant data base. Clearly, zinc addition has no impact on fuel performance based on this data up to an exposure of 41.7 GWd/MT. Figure 6 is another representation where fuel rod lift-off baseline data are compared with the combined effect of both HWC and zinc addition. Once again the combined effect of HWC and zinc addition is still within the non-additive experience base with lift-off values of < 25 $\mu$m [14]. Hot cell metallographic examinations from three plants, two zinc addition and the other a zinc + HWC plant, showed an average zirconium oxide thickness of less than 12 $\mu$m with peak values of 18 $\mu$m. Hydrogen pickup from these three fuel examinations were also within the experience band at less than 200 ppm. The hot cell examinations were on fuel with exposures in the range of 30.5 to 41.7 GWd/MT [14].

Neither zinc addition nor HWC has changed the total amount of fuel rod deposits, as shown in Figure 7, but zinc addition has changed the properties of the crud deposits significantly [16]. The outer brushed layer of the deposit was primarily $\alpha$-Fe$_2$O$_3$ but the inner adherent layer was a ferromagnetic spinel, primarily of zinc ferrite (ZnFe$_2$O$_4$) with some Ni [17,18]. Deposits were more adherent than previous experiences and the eddy current lift-off data from the fuel rods after zinc addition showed much higher values due to the greater ferromagnetic effect of the crud because of the presence of zinc [19]. The ferromagnetic property of the deposit enhanced the eddy current data giving exaggerated lift-off values. It must be noted that all of the lift-off data reported thus far have been corrected for the ferromagnetic effect electronically.

**Fuel Performance Experience Following Iron Addition**

It is generally recommended that BWRs control the feedwater iron, present as insoluble iron oxide coming from sources upstream of the clean-up system, to be in the range from 0.5 to 1.5 ppb. This recommendation is based primarily to optimize the shut down dose rates with zinc addition and HWC. The values come from both empirical observation and from a
shutdown dose rate model when optimized for feedwater iron level [14]. Keeping the feedwater iron level above 0.5 ppb is desirable to assure the formation of a sufficient amount of zinc spinel on fuel crud deposits so that most of the $^{60}$Co is retained on the fuel crud surfaces. However, in the early days of BWR operation, there were instances where the feedwater iron levels exceeded well above 1.5 ppb that resulted in the release of insoluble $^{60}$Co as particulates when rod movements or temperature transients occurred. In addition, higher levels of feedwater iron is not desirable as it could affect heat transfer across the crud layer at high exposures that could limit the corrosion performance of the Zircaloy-2 cladding material.

However, when BWR operators employed filter demineralizers in the clean-up system to control the feedwater iron level, in some cases, the feedwater iron dropped to values as low as 0.1 to 0.2 ppb. Since this amount of feedwater iron is inadequate to retain $^{60}$Co on fuel deposits, these plants had to resort to iron addition into the feedwater to maintain the iron level at the desired value of 0.5 to 1 ppb. The iron addition in BWRs was accomplished by injecting iron as an oxalate, acetate or as simple iron oxide into the feedwater system. Since the iron addition maintained the feedwater iron at the recommended values, no fuel surveillance programs were conducted to evaluate the fuel performance following iron addition.

**Fuel Performance Experience Following NMCA**

NMCA is a process where two noble metal chemicals containing Pt and Rh are injected into BWR water during hot shutdown when the temperature is held constant at the desired value between 121°C and 143°C for 48 hours.

1. **Laboratory and Halden Reactor Irradiation Tests With NMCA**

Prior to the plant NMCA application, an extensive laboratory evaluation was performed with Pt and Rh chemicals on Zircaloy-2 cladding that included i) nodular corrosion tests, ii) 316C water corrosion tests, iii) 400°C steam corrosion tests, and v) a Halden reactor irradiation test that used Pd. Detailed results of these tests appear elsewhere [20-22]. Treating Zircaloy-2 with Pd NMCA did not affect the corrosion or hydriding behavior in the Halden in-reactor test. Similarly, Zircaloy-2 specimens treated with Pt/Rh NMCA did not show any effect on the nodular or uniform corrosion resistance in laboratory tests. There was no significant difference between the hydrogen content of the NMCA treated fuel rod and the control fuel rod. All the results of this investigation were positive and justified NMCA application in a commercial BWR[21].

2. **Fuel Performance Evaluation at the Duane Arnold (DAEC) BWR**

The first NMCA application to a commercial reactor was performed in October 1996 at the Duane Arnold (DAEC) BWR just before EOC14 [20]. During the shutdown into a refueling outage, the reactor water temperature was held in the range of 129 to 143°C for 48 hours and Pt and Rh were each maintained in the reactor water at approximately 20 to 100 ppb. The total noble metal amount added to the reactor normalized to fuel area was 19.7 µg/cm². Subsequent ECP testing showed that the intended IGSCC mitigation requirements have been met at a low feedwater hydrogen concentration of 0.25 ppm.

The fuel deposit analysis at EOC 15 (after 18 months of plant operation) showed that the Pt and Rh profiles of one, two and 3 cycle bundles followed the crud profile, hence there was
no unusual deposition of Pt and Rh on fuel cladding surfaces. The rod average eddy current lift-off data for fuel rods treated with NMCA as compared to the data base for all other plants are shown in Figure 8. The Figure shows that the NMCA lift-off data are within the lift-off data base for non-NMCA plants and there was no discernible change in the hydrogen pick-up either, and hence it was concluded that NMCA had no impact on the corrosion behavior of Zircaloy-2 cladding material [22].

DAEC BWR performed a second NMCA application at EOC 16 with a fuel normalized noble metal input amount of 30 µg/cm² [23,24]. After 2 NMCA applications, the third cycle inspection at DAEC BWR was focused on 2 3-cycle fuel bundles, with burnups of 34 and 40.7 GWD/MTU, which were operated for 2 18-month cycles after the initial application in 1996 and one additional 24-month cycle after the re-application in 1999. Some local delamination of a surface layer, was visible over the 51 to 150 cm elevations as shown in Figure 9 [24]. However, the degree of spallation was mild and the spallation appeared to result mainly from flaking of a tenacious crud. The eddy current lift-off data were a little higher than the historical data base, largely due to a tenacious crud layer of 10 to 56 µm as confirmed by hot cell PIE at EOC 17 (i.e. 4.5 years of operation following first NMCA application in 1996). The zirconium oxide thickness under thick crud was relatively low, consistent with normal experience, Figure 10 [24]. A part of the crud layer appeared to be crystalline containing 30 to 35% zinc, consistent with the ZnFe₂O₄ phase. No failures were detected in any of the fuel rods at DAEC during the Cycles 15-17 monitoring period or to date.

3. Fuel Performance Evaluation at the Peach Bottom 2 (PB2) BWR

Peach Bottom 2 BWR had the highest fuel normalized noble metal input of 61.5 µg/cm² in the BWR fleet. The application was performed at EOC 12 and fuel surveillances were performed at EOC 13 and EOC 14. The results obtained at EOC13 after one post-NMCA cycle confirmed a mild increase in cladding lift-off, but still within the experience base for one and two cycle rods. However, some of the three-cycle high burn-up rods (~50 GWD/MTU) showed higher lift-offs and localized crud and or oxide delamination as shown in Figures 11 and 12 [24]. The low elevation crud/oxide spallation seen in Figure 11 was never seen in this plant again, or at any other NMCA plant. The zinc and the crud loadings were lower in this plant presumably due to lower feedwater zinc concentration of < 0.2 ppb during cyle 13.

A second poolside examination was performed at EOC 14 at PB2, and the lift-offs were within the non-NMCA experience base for both 2 and 3-cycle rods. However, there was some surface crud spallation at higher elevations, largely due to flaking of the crud layer, similar to the case at DAEC [24].

The EOC 14 crud scraping data showed zinc level in crud to be higher, approaching the zinc levels at DAEC 3-cycle rods, presumably due to the increased feedwater zinc levels during cycle 14. No fuel failures were observed in this plant following NMCA.

4. Crud Induced Fuel Failures in NMCA Plants

Browns Ferry-2, Browns Ferry-3 and another BWR/4 experienced apparent corrosion induced cladding failures, and failed fuel assemblies were removed during mid-cycle outages. Figure 13 shows appearance of fuel rods after brushing. Some unique features of these failures were that the affected rods were predominantly part length rods, cladding damage occurred at upper elevations of 228 to 254 cm for part length rods and 279 to 305 cm of full length rods. There was no excessive crud deposition, but there was evidence of crud
spallation at different elevations [25]. The primary failure locations at Browns Ferry-2 were heavily hydrided at elevations of 228 cm as evidenced by PIE.

Since Browns Ferry-2 and the second BWR are both NMCA plants and the failures occurred after about 6 to 7 months of NMCA operation, it became necessary to determine whether NMCA had any role in these fuel failures. However, the failure of thrice burned rods at Browns Ferry-3 was able to suggest that the corrosion failures were not a result of NMCA, because sibling rods from the same lot that were discharged after one cycle of operation without being exposed to NMCA, exhibited accelerated corrosion at both the 50 to 100 cm and 254 to 305 cm elevations [25]. The conclusion was that corrosion of the rods initiated before NMCA application.

**Fuel Performance Experience Following OLNC**

On-Line NMCA (OLNC), the next generation technology, is an improvement of conventional NMCA that can be implemented while a BWR plant is operating and generating power, thus avoiding the need to have any critical path time for the application. OLNC also provides other benefits such as quick ECP reduction during application, potential crack flank mitigation, isotopic release due to soft decontamination, that can lead to outage dose reduction.

The OLNC application uses only the Pt chemical and the fuel normalized input is limited to 10 μg/cm² of Pt per application. The OLNC application is performed at > 75% power and > 85% core flow [27] and hence one of the concerns was whether the noble metal would excessively deposit on high duty areas of the fuel cladding surfaces since the plant is in power operation. The fuel surveillances performed at the lead OLNC plant in Switzerland showed this to be not the case. The total fuel deposit loadings were low and the noble metal deposit amount on fuel was also low, there was no unusual accumulation of noble metal on the cladding surface [28]. This is understandable since the noble metal input in the case of OLNC is low and the reactor water Pt concentration during application is 1000 times lower (parts per trillion levels) [27] than the ppb levels of noble metals used during NMCA. The rod oxide lift-off values were within the non-HWC experience base. No fuel performance issues were detected as a result of HWC implementation.

The addition of zinc to BWRs showed that the fuel deposits were more adherent than previous experiences and the eddy current lift-off data exhibited much higher values due to the greater ferromagnetic effect of the crud because of the presence of zinc. The ferromagnetic property of the deposit enhanced the eddy current data giving exaggerated lift-off values. It is recommended that NMCA plants control the feedwater zinc levels below 0.4 ppb, and HWC plants control feedwater zinc levels below 0.6 ppb to minimize any potential crud spallations.
Since iron addition maintained the feedwater iron at the recommended values of 0.5 to 1.5 ppb, no fuel surveillance programs were conducted to evaluate the fuel performance following iron addition.

The post-NMCA fuel performance data show evidence of surface crud spallation and thick tenacious crud deposits at Duane Arnold and Peach Bottom-2. The magnetic properties of crud may have contributed to the increased lift-off seen in both plants. The hot cell examination of Duane Arnold 3 cycle rods showed that the zirconium oxide thickness under the thick crud was generally low at < 27 µm after 4.5 years of post-NMCA operation with high levels of zinc in the crud [9,24]. Also, there was no evidence of adverse effect on cladding hydriding due to long term exposure to NMCA, since the hydrogen content in the cladding was low at less than 70 ppm [9].

The highest noble metal input plant PB2 showed what appeared to be some oxide spallation in the bottom span during the first NMCA operating cycle [24], however, this behavior was never seen again in this plant or any other NMAC plant. As a precautionary measure the total noble metal input is now limited to 30 µg/cm² over the life of a fuel rod [26].

Minimizing the formation of thick and tenacious crud is desirable due to the concern to fuel integrity because of the potential increase in cladding temperature and corrosion rates [24]. Some BWR operators are now utilizing low feedwater iron inputs of < 0.5 ppb and < 0.4 ppb zinc in the feedwater under NMCA conditions in order minimize the tenacious ferromagnetic crud formation. However, there still are a few NMCA plants that still use > 0.4 ppb feedwater zinc because of the overwhelming benefits of zinc addition on radiation field reduction without any impact on long-term fuel performance.

The fuel surveillances performed at the lead OLNC plant in Switzerland showed the total fuel deposit loadings were low and the noble metal deposit amount on fuel was also low, there was no unusual accumulation of noble metal on the high duty regions of the cladding surface. The rod oxide lift-off values were well within the fleet experience base and no change in fuel performance or fuel reliability is expected with OLNC [28].

The demanding and improved modern chemistry evolutions have challenged the performance of fuel cladding materials in the recent years. However, the judicious control of water chemistry has enabled BWRs to achieve the much desired radiation field reduction, operating dose rate reduction and IGSCC mitigation while maintaining good fuel performance without affecting fuel reliability.

References

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Figure 1. BWR Reactor Water Conductivity Improvements in the Recent Years.

Figure 2. The Effective ECP Reduction with NMCA Over Hydrogen Water Chemistry.
Figure 3. Efficient ECP Reduction With On-Line NMCA (OLNC).

Figure 4. Rod Average Lift-off Data for Modern Cladding With and Without HWC [14].
Figure 5. Rod Average Lift-off Data for Cladding With and Without Zinc Addition [14].

Figure 6. Rod Average Lift-off Data for Cladding With HWC and Zinc Addition [14].
Figure 7. Measured Fuel Deposit Data for Deep Bed Condensate Treatment Plants [14].

Figure 8. Rod Average post-NMCA Lift-off Data from DAEC versus GE Data Base [22].
Figure 9. Post-NMCA Surface Crud Spallation at DAEC at EOC 17 [24].

Figure 10. Thick Crud Deposit on Surface Oxide of 3 Cycle Discharged Rods at DAEC [24].
Before Brushing

After Brushing

Figure 11. Potential Crud/Oxide Spallation at PB2 after NMCA at EOC 13 [24]. (This appearance was never seen again at this plant or any other plant)

After Brushing

Before Brushing

Figure 12. Surface Tenacious Crud Spallation at PB2 at EOC 14 [24].
Figure 13. Browns Ferry-2 Cycle 12 “Corrosion” Failed Rod Before and After Brushing [25].