ADMIRALTY BRASS MAIN CONDENSER TUBE DEGRADATION AT FITZPATRICK

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ABSTRACT

The James A. FitzPatrick Nuclear Power Plant is a General Electric Boiling Water Reactor (BWR 4 design) located on the southeast shore of Lake Ontario. The main condenser was re-tubed in 1994, with all admiralty brass condenser tubes replaced in-kind (the titanium impingement tubes were not replaced). The station operates with low feedwater hydrogen injection and Online NobleChem™ (OLNC) for mitigation of intergranular stress corrosion cracking (IGSCC) of reactor internals. Feedwater zinc injection is implemented for primary system (i.e., reactor recirculation system) shutdown radiation field control. The main condenser circulating water system is chlorinated to minimize microbiological fouling of the main condenser tubes.

Operating Cycle 21 ended in August 2014. During Cycle 21, the station experienced a number of large condenser tube leaks. Over 60 power reductions were performed since 2011 to isolate and plug leaking condenser tubes. Visual examinations showed that a number of the leaks were associated with longitudinal tube splits, some up to two feet in length. Some tubes were severed where the ends of the severed tube were flared outward. Significant wall thinning was also identified.

Increasing impurity levels in the condenser hotwell from condenser leaks challenges a BWR in maintaining low levels of detrimental anions (e.g., sulfate and chloride). These impurities enter the reactor vessel directly from the feedwater system and can initiate or accelerate intergranular stress corrosion cracking (IGSCC) of reactor internals. Further, other impurities from condenser leaks, such as silica, can impact BWR fuel performance.

This paper provides a summary discussion of the probable failure mechanism leading to the admiralty brass condenser tube splits, actions taken by the station to minimize impurity levels in the reactor coolant during Cycle 21, the effectiveness of these actions, and results of inspections in the fall 2014 refueling outage to assess fuel reliability and IGSCC of reactor vessel components from the unusual Cycle 21 chemistry conditions. The main condenser was completely re-tubed in the fall of 2014 with titanium.

1.0 INTRODUCTION

1.1 Plant Design Summary and Operational History

1.1.1 General Plant Design Summary

The James A. FitzPatrick (JAF) Nuclear Power Plant is a General Electric (GE) Boiling Water Reactor (BWR) that is located in the United States of America (USA) on the southeast shore of Lake Ontario. It is a BWR 4 design with a Mark I containment that began commercial operation in 1975. The plant is currently rated at about 2536 MWth (~860 MWe). A 5% power uprate was implemented in the 1990s. The current rated feedwater/condensate flow is about 1.41x10⁹ kg/sec.

The plant is designed with cascaded feedwater heater drains, moisture separators with reheat capability, and a reactor water cleanup system that can process up to about 15.5 kg/sec for an equivalent flow rating of about 1.1% of the current rated feedwater flow. The main circulating water system is once through cooling with the cooling water source from Lake Ontario.
The condensate treatment system is designed with eight deep bed demineralizers (no upstream filters). Each demineralizer vessel contains about 5.53 m$^3$ of ion exchange resin, 1.7 m$^3$ of which is an anion underlay. The ion exchange resins used are high capacity strongly acidic and strongly basic gel type resins, with the cation resin in the hydrogen form and the anion resin in the hydroxide form.

1.1.2 Condenser Design and History

The condenser original design parameters are shown in Table 1. The condenser contains two shells, each shell directly under a low pressure turbine. Each shell contains two sets of waterboxes. The bulk of the original tubes were admiralty brass. Type 304 SS was used for the top first three steam impingement rows and for the first row of tubes adjacent to the air removal section.

The non-condensable gases entering the condenser air removal section of a BWR contain primarily hydrogen and oxygen generated from radiolysis of the primary coolant, nitrogen and oxygen from air inleakage, and water vapor that is not condensed. Trace ammonia is also present, as N-16 formed in the reactor from neutron activation of O-16 will react with some hydrogen generated by radiolysis. Ammonia, being volatile, is carried over by the main steam to the condenser [1]. Main steam system radiation dose rates, due to the presence of N-16, at the original plant full power rating of 2436 MWth, ranged between 10 and 11 mSv/hr.

In 1984, all of the original Type 304 SS tubes were replaced with titanium (22 gauge, 0.090 cm wall thickness). The Type 304 SS, particularly the impingement tubes, were subject to external corrosion that was attributed to initial construction related activities.

In the late 1980s, the station began to experience chronic condenser leakage. Multiple eddy-current inspections over a number of refueling outages noted degraded tube material condition, caused by pitting, erosion, and corrosion. Wall loss was most severe at the outlet ends, up to 60% as measured in 1993. By the early 1990s, a considerable number of condenser tubes (primarily the admiralty brass tubes) were plugged (between 5 and 8% of the tubes per waterbox, see Figure 1). Some of the titanium steam impingement tubes were also plugged, although this was due in part to prevent gross leakage caused by damage from falling objects, such as lagging, and impingement baffles.

In 1994, all of the admiralty brass condenser tubes were replaced in-kind with new admiralty brass. Additional staking was installed inside the condenser shells to reduce the probability of damage from excessive vibration. This paper focuses on the performance of the admiralty brass tubes that were installed in 1994 and the apparent step change increase in tube material degradation that was observed between 2008 and 2011, culminating with a number of severe tube failures in 2013 and 2014 that led the station to replace all of the condenser tubes with titanium in their fall 2014 refueling outage. An interim action by the station implemented in the fall 2012 refueling outage was to sleeve the last 30 cm of each of the admiralty brass tubes, based on eddy current inspections that noted extensive wall thinning towards the tube ends. This interim action did not prevent tube splits that were observed to occur upstream of the sleeves.

1.1.3 Chemistry Control Strategies

From 1975 through 1988, the FitzPatrick station operated under normal water chemistry (NWC) conditions. No chemical additives for mitigation of intergranular stress corrosion cracking (IGSCC) of reactor recirculation piping or reactor internals were implemented during this period other than a onetime one weekend feedwater hydrogen injection test in 1985. The station did not add an external source of zinc injection for primary system (i.e., reactor recirculation system piping) radiation field control during this period, nor were any chemical additions made to the circulating water system for biological fouling or corrosion control.

Beginning in 1989, the station implemented feedwater hydrogen injection for IGSCC mitigation of the reactor recirculation system (RRS) piping and feedwater zinc injection for RRS piping radiation field
ontrol. Initial feedwater hydrogen injection rates equated to a feedwater hydrogen concentration of about 0.3 ppm but over the next ten years hydrogen injection rates were increased to achieve a maximum feedwater hydrogen concentration of about 0.6 ppm. The station operated for about a four year period at this higher concentration resulting in main steam line radiation levels increasing to 20-25 mSv/hr, as a result of higher N-16 carryover in the reactor vessel.

To reduce the impact of N-16 carryover and to mitigate IGSCC of key reactor internal components, the station implemented noble metal chemistry. The first generation noble metal injection process was implemented in November 1999 and again in September 2004. In August 2011, the station initiated the implementation of the second generation noble metal process (referred to as On-Line NobleChem™ or OLNC) and has been performing annual OLNC applications since that time. With noble metal chemistry, the station has been able to reduce feedwater hydrogen concentrations to 0.2 to 0.3 ppm, resulting in a reduction in N-16 radiation levels to levels comparable to NWC values.

In 1999, chlorination of the circulating water system (with sodium hypochlorite) was implemented to reduce biological fouling of the main condenser tubes in order to improve thermal performance. From the late 1990s through August 2014, one condenser water box was chlorinated for a two hour period each day, while maintaining a total residual chlorine (TRC) concentration of < 0.2 mg/l in the final plant effluent discharge (this was subsequently lowered to < 0.1 mg/l in 2008).

Typical circulating water system (i.e. Lake Ontario) chemistry data are shown in Table 2. The water is slightly basic, with a pH of 8.3. Lake Ontario water at times can also contain high levels of silt, particularly after storms or as the result of spring runoff.

2.0 KEY OPERATIONAL CHEMISTRY PARAMETER TRENDS

Reactor power from 2010 through 2014 is shown in Figure 2. Station refueling outages occur in the fall of even numbered years. There were over 60 power reductions since the beginning of 2011 to isolate a plant waterbox in order to locate and plug leaking condenser tubes. Most power reductions were down to 50 to 60% power. A power reduction is necessary to remove the suspected waterbox with the tube leak from service. Ideally, a waterbox can be removed from service at about 75% power, but lowering power to about 50% reduces dose rates to workers in the waterboxes locating tube leaks.

The first indication of a condenser tube leak is an increase in condensate inlet/hotwell conductivity. The station has continuous conductivity monitoring of the common condensate inlet (CDI) sample point (main condensate pump discharge) and each of the two condenser hotwells, via hotwell sample pumps. With hotwell sample pumps, the station can immediately tell which condenser has a tube leak. It cannot immediately be determined, however, which of the two water boxes per condenser has the leak. This can be done by removing from service, isolating and draining a waterbox and observing the hotwell conductivity trend.

The common CDI conductivity trend is plotted in Figure 3 and anion concentrations of each of the two hotwells are plotted in Figure 4. High CDI conductivity values can occur during plant outages due to air saturation. The CDI plot indicates the 2010 and 2012 refueling outages. All other conductivity spikes above the baseline value of 0.058 to 0.060 µS/cm are due to condenser leaks, with the largest leak occurring in early June 2014 when CDI conductivity increased to over 4 µS/cm.

Hotwell anion concentrations are used to accurately determine the condenser tube leak rate. For example, at 100% reactor power, a chloride concentration of 10 µg/l in the “A” hotwell would equate to a leak rate of about 20.2 m³/day. The calculated condenser leak rate at the peak CDI conductivity of 4.6 µS/cm (@ 30% reactor power on 6/1/2014) was about 233 m³/day.

In a BWR, the performance of the condensate treatment system and reactor water cleanup (RWCU) system are integral in mitigating the impact of condenser leakage on reactor internals corrosion and fuel performance. Further discussion will be included in Section 4.0 of this paper on strategies implemented
by the station to optimize the performance of the condensate treatment and RWCU systems to minimize the concentration of anions that are known to cause IGSCC.

Reactor coolant chemistry trends are shown in Figures 5 through 7. The increase in baseline reactor coolant conductivity values and the increased frequency in the number of conductivity spikes beginning in early 2012 (Figure 5) reflects the increasing baseline condenser leak rate and the increase in the number of power reductions for condenser leak isolation. The anions plot (Figure 6) shows both chloride and sulfate were controlled reasonably well, with most chloride values $\leq 1$ µg/l and most sulfate values $\leq 5$ µg/l. The concentration of sodium and calcium from about mid 2013 through the end of the operating cycle in August 2014 (Figure 7) were higher than the anion concentrations and had a greater influence on reactor coolant conductivity than chloride and sulfate. The peak reactor coolant conductivity value was about 8.0 µS/cm on 6/2/2014 (Figure 5). This conductivity value was influenced by a sodium concentration of 292 µg/l and calcium concentration of 416 µg/l. Chloride and sulfate concentrations for the same sample were 0.13 µg/l and 5.9 µg/l, respectively.

CDI soluble copper (Figure 8) has historically ranged from 0.6 to 2.0 µg/l and insoluble copper between 0.1 and 0.5 µg/l. The total copper average concentration from 1996 through 2014 was about 1.4 µg/l. At the nominal full power rated condensate flow, this equates to an annual average copper input of about 61.2 kg to the condensate treatment system. Based on the nominal composition of admiralty brass [2], this value is equivalent to an average corrosion rate of about 0.33 µm/year (steam side corrosion rate) of all 32,276 tubes (or about 0.026 % wall thickness loss per year). It is noted that copper loss also occurs on the circulating water side of the tubes, but copper measurements are not made of the circulating water. Silt present in the circulating water can act as an abrasive leading to wall thinning from the circulating water side. It is expected that some silt settles in the tubes due to the fact that the tubes are long. Towards the outlet ends, the tube fluid velocity can be larger due to the settled silt (narrower diameter), leading to greater outlet end internal erosion.

### 3.0 CONDENSER TUBE FAILURE EVALUATION

As shown in Figure 9, following the condenser re-tubing in 1994, the first tube leaks were reported in 1999. By 2002, about 1.8% of the tubes in each waterbox were plugged. There was an extended period between 2003 and 2008 when there were few tube leaks. This was followed by a three year period (2008-2011) where the number of plugged tubes in each waterbox increased significantly. During Refuel Outage 19 (RFO19, fall of 2010), 100% eddy current testing confirmed significant wall thinning of the admiralty brass tubes.

A Root Cause Evaluation by the station in 2012 concluded that the locations of the tube failures in the current condenser correspond with similar locations of tube failures in the original condenser before the 1995 re-tubing. The service time of the original admiralty brass tubes in the main condenser before re-tubing was approximately 5,940 days, and the service time of the current condenser (at the time of the station evaluation on 6/20/2011) was 5,653 days. Further, the trend of the degradation is similar as shown by the tube plugging history presented in Figure 10. Figure 10 illustrates that the degradation trend of the second generation of brass tubes was similar to what was observed prior to the condenser being re-tubed in 1995, and includes a predicted rate of degradation based on collected data. Tubes are plugged based on a 60% wall thickness loss, as determined by eddy current testing. The 10% tube plugging limit shown in this plot is an industry rule of thumb. The 9% tube plugging limit shown in Figure 9 is a FitzPatrick specific plant thermal performance limit.

For the original condenser, there were no data points prior to about 3,000 hours of operation. Conversely, the second generation of admiralty brass condenser tubes had recorded leakage within 4 years and experienced tube plugging very early in life, which was attributed to localized damage mechanisms such as lagging failures, fretting and pitting. General wall thinning, wastage, or linear splits were not identified as a relevant damage mechanism at that time (1998-2002). Based on the trend shown in Figure 10, the
predicted 10% total tube plugging level, where there essentially is no remaining margin, occurred between Refuel Outages RFO20 and RFO21 (2012-2014) where the margin above the minimum required number of tubes will be lost almost completely.

The degradation trend of increased metal loss at the outlet end of the tubes (from eddy current measurements in RFO19), shown in Figure 11, is consistent with what was reported in 1993 by the station prior to the condenser being re-tubed in 1995. An example of outlet end erosion is shown in Figure 12.

To support the station’s Root Cause Evaluation, six separate tube sections were received for examination (Figure 13) by Structural Integrity Associates in September 2012. One of the tube sections was a tube where a linear split occurred (the tube samples were obtained during a mid-cycle power reduction). In the operating cycle following the SI evaluation, additional tube failures occurred where a tube split was identified by visual examination or assumed based on the calculated leak rate. The tube section samples evaluated by SI are identified as follows:

- Outlet end tube marked “D-95-2 outlet” (~31.7 cm long)
- Outlet end tube marked “A-39-28 outlet” (~29.8 cm long)
- Linear split tube marked “A-39-28 linear split”
  - Cut into 3 sections designated:
    - “6-7” (~39.3 cm long)
    - “7-8” (~54 cm. long)
    - “8-9” (~51.4 cm long)
- Exemplar tube marked “Original tube sample from 1994 (never installed)” (~16.5 cm long)

Mechanical scratches and marks were observed on the OD of all of the tubes that had been removed from service. There were obvious signs of OD damage from tube removal and where supports had apparently been located. Examples of these markings are shown in Figure 14.

Three ring sections were taken for chemical composition analysis, one from the exemplar, one from the linear split, and one from outlet tube D-95-2.

One transverse section from each outlet end tube was mounted in epoxy, polished and etched for metallurgical evaluation. The remaining pieces of the outlet end tubes were indexed and cut into several 2.54 cm ring sections to facilitate wall thickness profile measurements. The linear split tube was received in 3 pieces. Two fracture surface ring samples were removed from two of the fish mouth openings from piece “7-8”, mounted and prepared for metallurgical evaluation. One of the remaining fish mouth openings was removed and used for Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analysis of the fracture surface. An additional ring sample where the flaw was visible from the OD surface but was not expected to be through-wall was removed and mounted also. Two ring sections were taken remote from the through-wall failure from piece “6-7” for additional SEM analysis of the OD flaw.

Figure 15 shows the through-wall failure at a fish mouth opening on linear split tube “7-8” (transverse section). The fracture appears mostly intergranular, and displays a small amount of branching through the thickness. The microstructure is unremarkable.

Figure 16 shows a transverse section with an OD initiated crack approximately 75% through the thickness. The crack is mostly intergranular and has a small amount of branching. This crack resembles the textbook image of stress corrosion cracking (SCC) in admiralty brass as shown in Figure 17 (taken from Reference 5), however, the corrosion fatigue mechanism in brass materials also closely resembles SCC. The two are effectively indistinguishable based on observation of the crack morphology.
SEM analysis was performed to interrogate the fracture surface. First, the sample was evaluated with an optical microscope to identify areas of interest. It was clearly seen that the crack like flaw was OD initiated with the final rupture occurring at the ID as shown in Figure 18. The fracture surface was covered with a dull reddish oxide and other surface debris while the area of final rupture was very shiny and brass colored. Approximately 17 distinct longitudinal ridges were observed on the fracture surface. Figure 19 shows an SEM image of the fracture surface showing the high amount of surface oxide, the distinct longitudinal ridges and the final rupture surface.

Figure 20 provides a higher magnification of the final rupture surface which shows a smeared surface covering a dimpled rupture morphology. Dimpled rupture is indicative of a ductile tensile overload failure.

The EDS results of three sample locations are shown in Table 3. Areas 1a and 1b are from the center of the fracture surface, and Area 1c is from the ID area of final rupture. The fracture surface was not cleaned prior to the EDS analysis. The results show that the fracture surface at Areas 1a and 1b generally contained a high amount of oxygen, copper and zinc, about 1% of tin, and small amounts of other elements. The high oxygen content is consistent with the observed surface oxide, and the small amounts of other elements are likely the result of surface contamination. The final rupture at Area 1c, had a significantly lower concentration of oxygen.

The observed linear split appears to be due to a combination of tube wall thinning and external cracking, most likely from SCC or corrosion-fatigue. The single longitudinal crack in the linear split tube was OD initiated. There is only one crack initiation site around the circumference of the linear split tube with rare occurrences of secondary cracking very near the main crack. The longitudinal crack was very straight, and appeared to be on the bottom half of the tube based on observed ID deposits. The linear split failure was the result of tensile overload on the remaining tube wall ligament, which was approximately 0.051 mm thick. A literature review suggests that SCC can occur in Admiralty Brass condenser tubes due to the presence of ammonia [2], and is more likely to occur near the air removal section of the condenser. As stated in Section 1.1.2, trace ammonia does form in the reactor vessel and is carried over in the main steam to the condenser. However, the concentrations are not believed to be high enough to initiate SCC (also, it is noted that the first few rows of tubes adjacent to the air removal section at FitzPatrick were titanium). The presence of oxygen significantly reduces the concentration of ammonia needed to facilitate SCC, and the surface oxides observed on the condenser tubes confirms the presence of oxygen. Linear splits were not reported as a failure mode of concern prior to re-tubing the condenser in 1995. Based on the extent of cracking and wall thinning observed from the sample, it was concluded that linear split failures would continue to occur, perhaps at a greater frequency until the condenser tubes are replaced.

All of the tube samples exhibited effects of erosion and probably erosion-corrosion. The measured average wall thickness values ranged from 0.41 to 0.71 mm; a significant reduction from the nominal 1.25 mm wall. The thinning was fairly uniform around the circumference and along the length of the samples. The wall thickness measurements confirmed the station predicted degradation trend (eddy current testing results) for tube outlet end erosion. Higher rates of tube degradation were postulated as more tubes are plugged, partially due to the associated increase of flow in each tube.

The station’s interim action based on the evaluation of the tube samples and eddy current testing results was to sleeve the last 30 cm of the outlet ends of the brass tubes in the fall 2012 refueling outage with Copper-Nickel sleeves, as this was thought that it could help extend the condenser life until the fall 2014 outage, allowing for sufficient time to procure an alternate tube material and perform the required design modifications. In the operating cycle following the tube liner installation, nearly 50 power reductions were performed for tube leak isolation, indicating that the sleeves were not effective in preventing leakage, although a number of the leaks that occurred after the 2012 refueling outage were due to linear tube splits that were located upstream of the sleeves.
The Limerick station (dual unit BWR) and the River Bend station (single unit BWR) are plants in the U.S. that have admiralty brass condenser tubes. These stations are still operating with their original condenser tubes (greater than 15 years old) and have not experienced tube splits and significant wall thinning as FitzPatrick. Vermont Yankee (single unit U.S. BWR that is now permanently closed as of December 2014) did experience outlet end wall thinning of their brass tubes and did install outlet end sleeves. The Columbia station, also a single unit U.S. BWR, replaced their admiralty brass condenser in 2011 with a unit containing all titanium tubes. Both Columbia and Vermont Yankee experienced chromic condenser leakage throughout their operating history.

4.0 CHEMISTRY STRATEGIES TO MITIGATE IMPACT OF DEGRADED CONDENSER MATERIAL CONDITION

This section of the paper describes actions by the station to manage reactor coolant chemistry in order to minimize the potential of IGSCC of reactor internals. The condensate treatment system at FitzPatrick does not have filters upstream of the deep bed demineralizers. Historically, when there were no condenser leaks, the nominal demineralizer resin life was between two and three years (resins are replaced, not chemically regenerated). Resin changes were typically performed based on total anion resin cumulative ionic loading as well as increasing reactor coolant sulfate values. The sulfate source would be from cation resin decomposition products with the likely source being from the oldest condensate demineralizer.

Without upstream filters, iron crud from the corrosion of steam side carbon steel surfaces accumulates in the resin beds leading to increasing differential pressure. As a result, the resin beds must be periodically cleaned. Resin beds are transferred out of the service vessel and are subjected to an ultrasonic resin cleaning process and then returned to the service vessel. Because the resins are mixed during resin transfers and resin cleaning, it is not possible to re-establish fixed ion exchange zones that existed in the resin bed prior to the first resin transfer from the service vessel to the cleaning process. This is not a significant issue when there is minimal ionic loading on the demineralizer resin, but with the ionic loading from condenser leakage, it was recognized that disturbance of the ionic exchange zones by bed mixing would result in premature resin replacements due to equilibrium leakage. In the spring of 2013, it was decided to suspend all resin cleaning operations and operate the beds until the first sign of anionic leakage and then replace the beds with new resins. As the frequency of condenser leaks increased, resin life was reduced to between 80 and 100 days (i.e., from normal life of two to three years), equivalent to about 20% cumulative anion resin ionic loading. This strategy was key in controlling increases in reactor coolant anions and was also beneficial in reducing final feedwater iron (Figure 21), as the resin cleaning process does not remove all of the accumulated iron in the resin bed, resulting in release to the effluent of some filtered iron in the resin beds. From a fuel reliability perspective, lower feedwater iron results in lower fuel crud deposits reducing the potential for fuel crud/corrosion failures.

Copper removal by the condensate demineralizers was impacted by the presence of elevated cations from condenser leakage, specifically calcium, which has a higher ion exchange selectivity than divalent copper. Increasing feedwater copper concentrations are a fuel reliability concern as copper has been linked in the past to BWR fuel crud/corrosion failures. Feedwater copper levels began increasing in 2012, as the frequency of condenser leakage increased, but decreased in 2013 after the station suspended resin cleaning in conjunction with implementing a shorter resin life (Figure 21), as the resin cleaning process does not remove all of the accumulated iron in the resin bed, resulting in release to the effluent of some filtered iron in the resin beds. From a fuel reliability perspective, lower feedwater iron results in lower fuel crud deposits reducing the potential for fuel crud/corrosion failures.

For the RWCU Filter/Demineralizers (F/Ds), the station changed the precoat material in early 2014 from an anion enriched precoat material (Epicor PD-23H) to a cation enriched precoat material (Epicor 2110-
H). Epicor 23H is an all resin premix, with a cation to anion resin ratio (dry weight basis) of 2:3. Epicor 2110-H is a resin/fiber premix with a resin to fiber ratio of 9:1 (dry weight basis), with the cation to anion resin ratio (dry weight basis) of 2:1. The change to a precoat with a higher cation to anion resin ratio was to better control reactor coolant conductivity, as conductivity was being impacted primarily from cation leakage (mainly sodium) from the condensate demineralizers. The use of a large anion underlay in the condensate demineralizers was effective in controlling sulfate and chloride leakage from condenser circulating water ingress at the expense of increased sodium leakage.

A modification implemented by the station in the fall 2012 refueling outage to improve feedwater hydrogen availability turned out to be integral in minimizing IGSCC mitigation of the reactor vessel internals during the period of elevated condenser leakage in 2013 and 2014. The modification removed the trip interlocks to allow feedwater hydrogen injection to be in service without the offgas treatment system (recombiner and charcoal beds). The modification was intended for the plant to start feedwater hydrogen injection at lower power (~5%) and to remain in service at full power should there be unexpected trips of the offgas treatment system. Feedwater hydrogen injection in a BWR with OLNC chemistry results in low total oxidant concentrations at the surface of the deposited noble metal catalyst corresponding to very low electrochemical corrosion potentials at which IGSCC is mitigated.

When a waterbox is isolated and being drained, once the water level in the waterbox reaches the level of the leaking tube, air inleakage to the condenser increases. The offgas treatment system at FitzPatrick is flow limited, with elevated offgas flows of greater than about 1.41 m³/min resulting in offgas treatment system trips. For large tube leaks, the offgas treatment system would trip as a result of increasing air inleakage when a waterbox was drained. Prior to the 2012 modification, a trip of the offgas treatment system would trip feedwater hydrogen injection, resulting in 12 to 24 hours of lost hydrogen availability due to the time needed to locate and plug leaking condenser tubes. The modification to remove the offgas treatment system trip interlock eliminated many hydrogen injection system trips, allowing the station to maintain constant reducing conditions in the reactor coolant.

5.0 OBSERVATIONS DURING FALL 2014 REFUELING OUTAGE

This section of the paper provides a brief summary of nuclear fuel inspections and in-vessel visual inspections to assess the impact of extended plant operation with condenser tube leakage.

A detailed fuel examination at the end of the cycle was performed to assess the impact from the numerous condenser tube leaks and the associated power maneuvering transients. There were no fuel failures in the cycle. The maneuvering transients resulted in relatively high Feedwater metals inputs (along with periods of higher zinc injection rates) and added crud redistribution to higher powered fuel. While the inspection found higher than normal fuel cladding liftoff (thickness of the cladding oxide + the tenacious crud) in some bundles, most of the liftoff was due to crud, and corrosion appeared to be normal. Liftoffs were still well within the successful industry experience base. No impact on fuel reliability is expected.

In-vessel visual examinations (IVVI) are performed each refueling outage in order to ensure the structural integrity of the reactor vessel internals. For the 2014 refueling outage, a total of 305 exams of reactor vessel internals were completed. Overall, only one new indication was found during the 2014 refueling outage. This was on the moisture separator that is located above the reactor core, and is not mitigated under hydrogen water chemistry. No previous identified flaws showed any change, indicating that the chemistry control strategies to mitigate IGSCC were effective, despite the many challenges from the degraded main condenser material condition.

6.0 CONCLUSIONS

1. The tube plugging trends for both the original condenser (1975) and the retubed condenser (1994) suggests that the operating life of admiralty brass condenser tubes at FitzPatrick is about 15 years.
Some other BWRs in the U.S. have been able to operate for a significantly longer time period with their original admiralty brass condenser tubes.

2. All in-service tube samples that were examined exhibited effects of erosion and probably erosion-corrosion. The measured average wall thickness values ranged from 0.41 to 0.71 mm; a significant reduction from the nominal 1.25 mm wall.

3. Linear tube splits appear to be due to a combination of tube wall thinning from the Inside Diameter (ID) and external cracking, most likely from SCC or corrosion fatigue. There was no apparent pattern to the location (distance from the inlet or outlet end) of the linear splits.

4. Chemistry actions to manage the condensate and reactor water cleanup treatment systems were effective in maintaining low concentrations of anions in the reactor coolant that are known to cause IGSCC of reactor internals. IVVI exams found no change in any previously identified flaws. Fuel exams showed normal corrosion levels.

7.0 REFERENCES


NOMENCLATURE

BWR – Boiling Water Reactor
CDI – Condensate Demineralizer Inlet
EDS – Energy Dispersive X-ray Spectroscopy
F/D-Filter/Demineralizer
GE – General Electric
ID – Inside Diameter
IGSCC – Intergranular Stress Corrosion Cracking
IVVI – In-vessel Visual Inspection
OD – Outside Diameter
OLNC -On-line NobleChem™
RFO – Refueling Outage
RWCU -Reactor Water Cleanup
SCC – Stress Corrosion Cracking
SEM – Scanning Electron Microscope
SHE – Standard Hydrogen Electrode
U.S. – United States

Table 1 Original Condenser Design Parameters

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<th>Feature/Parameter</th>
<th>Value</th>
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<tr>
<td>Number of Condenser Shells</td>
<td>2 (Condenser A, Condenser B)</td>
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<tr>
<td>Number of Water-Boxes Per Condenser Shell</td>
<td>2 (A1, A2; B1, B2)</td>
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<tr>
<td>Number of Tube Passes</td>
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<td>Total Number of Tubes/Total Surface Area</td>
<td>36,860/17,196 m²</td>
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<tr>
<td>Tube Dimensions</td>
<td>2.22 cm (Outside Diameter, OD), 18 gauge, 13.4 meters long</td>
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<tr>
<td>Circulating Water Tube Fluid Velocity</td>
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| Tube Material                  | 32,276 – Admiralty Brass; 4,584-304 SS (Impingement Tubes and
Table 2 Circulating Water System Chemistry Data

<table>
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<th>Parameter</th>
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<td>Conductivity</td>
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</tbody>
</table>

Table 3 EDS Result of Fracture Surface from Linear Split Tube (20 keV accelerating voltage)

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area 1a</td>
</tr>
<tr>
<td>O</td>
<td>8.019</td>
</tr>
<tr>
<td>Mg</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>0.548</td>
</tr>
<tr>
<td>Si</td>
<td>.0690</td>
</tr>
<tr>
<td>Cl</td>
<td>0.355</td>
</tr>
<tr>
<td>Fe</td>
<td>0.402</td>
</tr>
<tr>
<td>Cu</td>
<td>60.347</td>
</tr>
<tr>
<td>Zn</td>
<td>28.412</td>
</tr>
<tr>
<td>Mo</td>
<td>0.273</td>
</tr>
<tr>
<td>Sn</td>
<td>0.954</td>
</tr>
</tbody>
</table>

Figure 1 FitzPatrick Tube Plugging History for Original Condenser (1985-1993)
Figure 5: FitzPatrick Reactor Coolant Conductivity

Figure 6: FitzPatrick Reactor Coolant Anions

Figure 7: FitzPatrick Reactor Coolant Cations
Figure 8 FitzPatrick CDI Copper

Figure 9 FitzPatrick Tube Plugging History (1995-2012)
Figure 10 FitzPatrick Condenser Plugging History vs. In-service Time

Figure 10 Legend:

1) NYPA = New York Power Authority (Original Condenser 1975-1994)
2) Current = 1994 condenser retube (as of R19 in 2010)
3) Recommended – Eddy Current Vendor reviewed R19 eddy current data and recommended further tube plugging that was eventually performed mid-Cycle 20)

Figure 11 FitzPatrick Condenser Tube Wall Thickness along the Length
Figure 12 FitzPatrick Condenser Tube “Outlet End Erosion”

Figure 13 FitzPatrick As-Received Tube Sections
Figure 14 OD Mechanical Damage and Apparent Support Location

Figure 15 Transverse Cross Section of Linear Split (ammonium persulfate etchant)
Figure 16 Partial Through-wall Crack from Remote Section of Linear Split Tube “7-8”
(ammonium persulfate etchant)

Figure 17 SCC Crack in Uninhibited Admiralty Brass [3]
Figure 18 Stereoscopic (low power optical) Image of Fracture Surface

Figure 19 SEM Image of Fracture Surface

Figure 20 SEM Image of Final Rupture Surface
Figure 21 FitzPatrick Feedwater Iron

Figure 22 FitzPatrick Feedwater Copper