BWR SOURCE TERM MANAGEMENT – STRATEGIES AND RESULTS AT GENERAL ELECTRIC-DESIGNED BWRS

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ABSTRACT

Source term management and dose rate reduction strategies at the GE-designed BWRs operating today have evolved over the past several years. This paper reviews the past and current strategies, the implementation of new technologies, and results for the operating fleet. Various measures, such as oxygen injection and enhanced condensate filtration and/ordemineralization, have been employed to reduce corrosion products transport from balance-of-plant systems. These advances, along with injection of natural and depleted zinc oxide to the reactor system, chemical decontamination of the piping systems, and cobalt source term removal, have had some degree of success. The implementation of hydrogen injection for the mitigation of intergranular stress corrosion cracking (IGSCC) of piping and reactor internal components has had an impact on operating and shutdown dose rates. However, the reduced injection of hydrogen coupled with noble metal addition technologies has had a positive impact on BWR dose reduction.

Today's operating BWRs follow the EPRI BWR Water Chemistry Guidelines for water chemistry optimization practices. This paper also explores the guidance within the Guidelines document for reducing occupational exposure while maintaining IGSCC mitigation practices and supporting optimum fuel performance. An evaluation of the industry's diagnostic parameter of the soluble reactor water Co-60/soluble zinc ratio and its impacts on piping dose rates and future recommendations are provided. Chemistry's role in dose reduction has been significant for the BWR fleet and will continue to play an important part in plant operation as the fleet moves into sixty years, or more, of safe and reliable operation.

1. INTRODUCTION

BWR water chemistry has evolved from essentially pure, relatively oxidizing water to the current programs, which include hydrogen injection for IGSCC mitigation, depleted zinc oxide (DZO) addition to minimize shutdown dose rates, and noble metal chemical application (NMCA, NobleChem™) or On-Line NobleChem™ (OLNC) to reduce main steam operating dose rates. A major objective of this evolution has been to achieve improved BWR chemistry control to extend the operating life of the reactor piping, vessel and internals, and balance-of-plant materials and turbines, while controlling costs to retain economic viability. The injection of hydrogen and application of noble metals cause chemistry in the reactor environment to change from oxidizing to reducing, resulting in changes in the piping oxide film from a relatively thick, loose hematite form to a thin, dense magnetite form. Zinc promotes formation of a more protective spinel-structured oxide film on stainless steel, especially under reducing conditions. The spinel structure favors incorporation of zinc over cobalt. Radiation dose rates are lowered by keeping Co-60 from incorporating in the oxide film.

BWRVIP-190: BWR Water Chemistry Guidelines – 2008 Revision [1] provides the current bases, requirements and optimization goals for water chemistry control for General Electric's BWR-2 through BWR-6 plant designs. (EPRI is currently assessing the applicability of these guidelines to the ABWR.) Guidance is provided to optimize water chemistry to mitigate IGSCC, avoid fuel crud and corrosion failures and control operational chemistry to minimize radiation fields. BWRVIP-190 [1] recommends feeding sufficient zinc to achieve a Co-60(s)/Zn(s) ratio of <2E-5 μCi/ml/ppb in the reactor water. However, the Guidelines recognize that chemistry control must be balanced to achieve all objectives. While the injection of DZO has been beneficial in reducing radiation fields, if feedwater zinc becomes too high it can result in fuel crud spallation, which may be an indicator of increased risk of fuel failures. The *Fuel Reliability Guidelines: BWR Fuel Cladding Crud and Corrosion* [2] provided the technical bases for chemistry control for fuel reliability that have been incorporated in BWRVIP-190 [1].

Significant progress has been made by the BWR industry in reducing feedwater iron. This has resulted in an increase in the ratio of reactor water zinc to feedwater zinc, allowing the target Co-60(s)/Zn(s) ratio to be achieved at lower feedwater zinc concentrations. Feedwater iron reduction has also lowered cobalt transport from the condensate to the reactor, thus reducing the cobalt source term. Additional progress in cobalt source term reduction has been made by replacement of balance-of-plant and reactor internal components constructed using Stellite® for hard-facing with alternative materials that contain significantly less or no cobalt.

Data presented in this paper were collected under the EPRI BWR Chemistry Monitoring and Assessment program.

2. BWR CHEMISTRY MONITORING AND ASSESSMENT

Under the ongoing BWR Chemistry Monitoring and Assessment effort, EPRI collects and compiles information on plant design, operating practices, chemistry control, IGSCC mitigation and monitoring strategies, along with detailed chemistry and radiation dose rate data. Currently, forty-nine (49) North American, Asian and European BWRs participate in this program, as indicated in Figure 1. Data are routinely evaluated to assess BWR plant chemistry performance, operating experiences and practices relative to the *EPRI BWR Water Chemistry Guidelines – 2008 Revision* [1]. Periodic electronic and formal technical reports are issued [3].

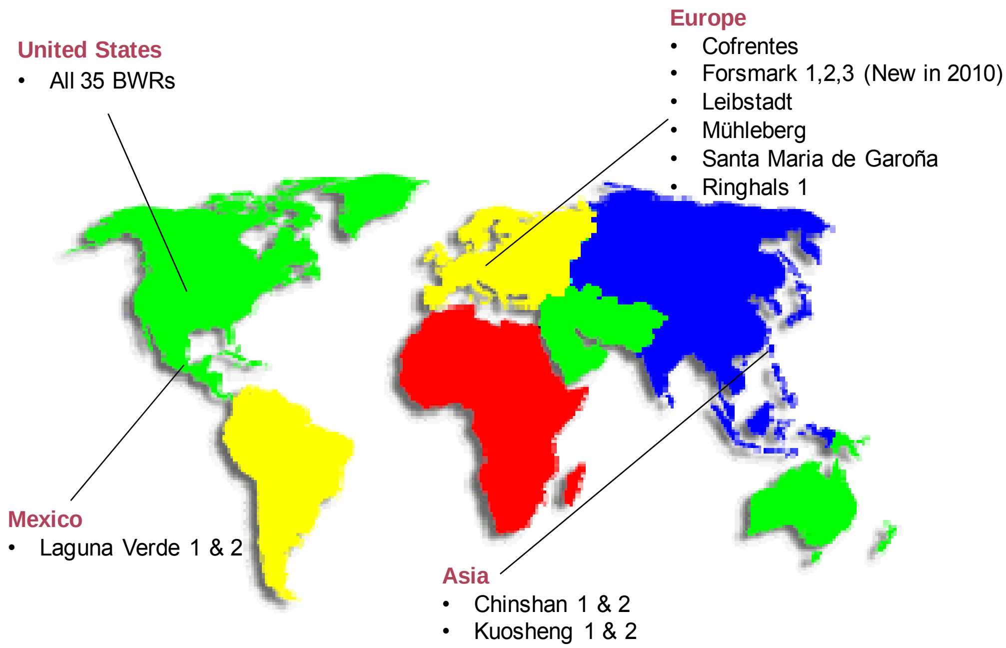

Figure 1. BWRs Participating in EPRI BWR Monitoring and Assessment Program

3. BWR CHEMISTRY REGIMES

The history of normal water chemistry (NWC), hydrogen water chemistry (HWC), zinc injection, noble metal chemical application (NMCA and OLNC) at participating BWRs is shown in Figure 2. HWC was developed and implemented to mitigate IGSCC of stainless steel and nickel based alloys used to construct reactor coolant system piping and vessel internals. However, at feedwater hydrogen concentrations of 1 – 2 ppm (moderate HWC, HWC-M) required for IGSCC mitigation of reactor internals, main steam line radiation levels were observed to increase by up to six times greater than the level without hydrogen injection. The source of increased steam radiation is primarily N-16 (7.1 second half-life) from formation of volatile forms of nitrogen, such as ammonia, produced under the reducing chemistry environment established by HWC.

Noble metal application involves the deposition of small amounts of catalytic material, such as platinum and rhodium, on the wetted surfaces in contact with the reactor coolant to catalyze recombination reactions of hydrogen with oxidants (oxygen and hydrogen peroxide) at those surfaces. When sufficient hydrogen is injected to achieve a molar ratio of hydrogen to total oxidant in reactor water greater than two, the ECP (electrochemical corrosion potential) response of the treated surfaces drops to <460 mV(SHE). This ECP response is achieved at low feedwater hydrogen concentrations (usually between 0.1 and 0.3 ppm), about an order of magnitude lower than those required by HWC for IGSCC mitigation of reactor internals. A major advantage of noble metal application is that there is little or no increase in main steam line radiation from N-16 activity at these low hydrogen injection rates. In addition, the low ECP established at the surfaces along with zinc injection (discussed below) results in a lower rate of incorporation of Co-60 into the oxide film, thus lowering radiation fields.

Use of the OLNC process began in 2005, and the rapid adoption of this technology is indicated in Figure 2. OLNC injects only platinum when the plant is operating at or near full power, and reapplication is recommended every 11 to 16 months. With OLNC, low feedwater hydrogen concentrations are required to achieve low ECP, and operational dose benefits are realized as with NMCA. As OLNC is adopted, the number of plants operating under NWC, HWC and NMCA will continue to decrease.

Addition of zinc into the reactor coolant is a demonstrated means of reducing Co-60 buildup in primary piping corrosion films. This has the major benefit of reducing radiation dose rates in the drywell, thus reducing radiation exposure during outages. The benefits of zinc injection are well documented in the BWR Water Chemistry Guidelines [1] and the BWR Chemistry Performance Monitoring Report [3], and can be summarized as follows:

- Zinc inhibits the corrosion of stainless steel and Inconel™ in the primary system surfaces.
- Zinc competes with cobalt for the same tetrahedral crystal sites in spinel corrosion films, thus lowering the cobalt composition in the film.
- Zinc suppresses the release of established Co-60 from both the in-core cobalt-bearing materials and the iron-based deposits that reside on the fuel cladding.

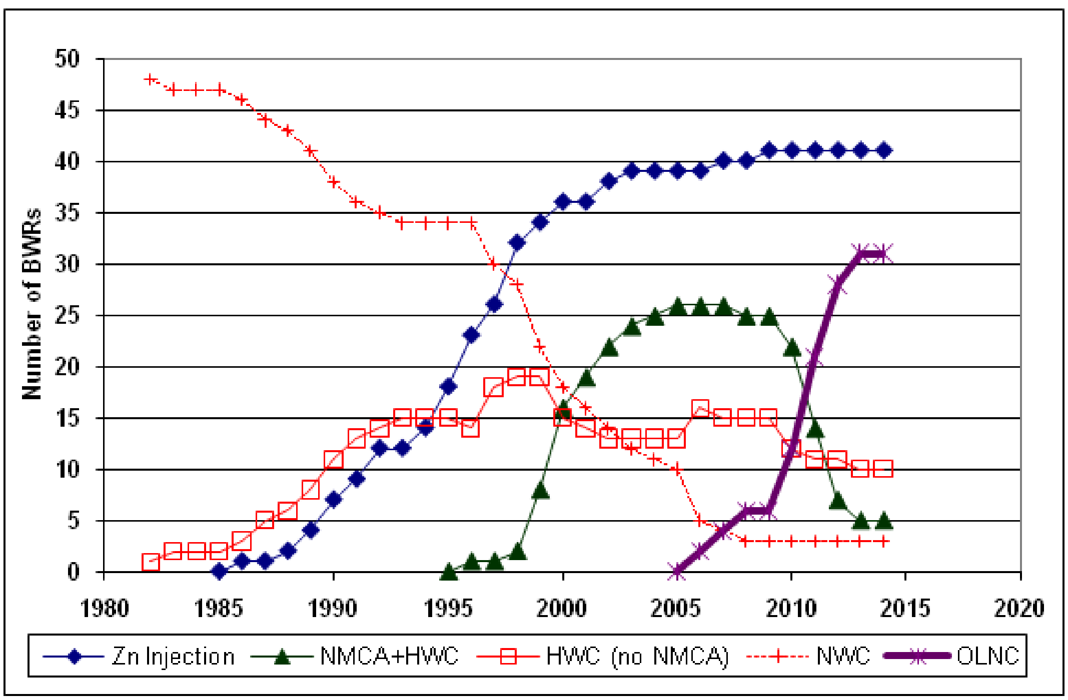

Figure 2. History of BWR Chemistry Programs

Initially, NZO (natural zinc oxide) was added to the feedwater, but this had the side effect of increasing Zn-65, produced from activation of the naturally occurring Zn-64 isotope, which added to the radiation field source. This led to the introduction of depleted zinc oxide, having less than 1% Zn-64 compared to about 48% in natural zinc oxide; consequently, the production of Zn-65 was significantly reduced. As of June 2010, forty-one (41) BWRs, including all U.S. BWRs, were adding DZO to the feedwater for drywell radiation field control. The progress of implementation is shown in Figure 2.

4. BWR WATER CHEMISTRY GUIDELINES AFFECTING SHUTDOWN RADIATION FIELD CONTROL

BWRVIP-190 [1] provides good practice values for reactor coolant soluble Co-60 activity, reactor coolant soluble Co-60 to soluble zinc ratio and control parameter values for feedwater metals concentrations. These values are summarized in Table 1.

Table 1. Summary of Good Practice and Control Parameter Values

Parameter	Good Practice Value	Control Parameter Value
Reactor Coolant Soluble Co-60, µCi/ml	<5E-5	
Reactor Coolant Soluble Co-60/Soluble Zinc Ratio, µCi/ml/ppb	<2E-5	
Feedwater Zinc, ppb (HWC-M)		<0.6 ppb (quarterly average)
Feedwater Zinc, ppb (NMCA+HWC, OLNC+HWC)		<0.5 (quarterly average) <0.4 (cycle average)
Feedwater Iron, ppb	0.1 – 1.0	>5.0 (Action Level 1)
Feedwater Copper, ppb	<0.05	>0.20 (Action Level 1)

The value of < 5E-5 µCi/ml for reactor water soluble Co-60 activity was part of the Optimum BWR Water Chemistry Parameters originally specified by General Electric in the 1990s and later incorporated in the EPRI BWR Water Chemistry Guidelines. The basis for the soluble Co-60 to soluble zinc ratio good practice value of < 2E-5 µCi/ml/ppb was that plants with reactor recirculation piping dose rates less than 100 mR/hr after the first cycle following NMCA met this value, as is discussed later. This good practice recommendation was later extended to HWC-M plants [1]. Most plants have been successful in meeting the ratio goal, as shown in Figure 3.

The basis for establishing < 0.4 ppb cycle average feedwater zinc concentration for noble metals plants was that fuel surveillances showed increased potential for tenacious crud (zinc ferrite) spallation on fuel surfaces when operating above this value. A quarterly average value of < 0.5 ppb is allowed to account for higher zinc demand in response to increased Co-60 activity in the first two to three months following a noble metal application and/or the need to ensure sufficient zinc in the beginning of an operating cycle following a chemical decontamination. The <0.6 ppb cycle average value for HWC-M plants was based on the concern that the need to operate above this value was an indication of excessive iron inputs.

The Action Level 1 value for feedwater iron of >5 ppb is based on avoiding fuel concerns related to excessive iron loading on the fuel cladding. The long term recommendation for feedwater iron is 0.1 – 1.0 ppb [1]. The basis for this recommendation is that minimizing crud deposits is beneficial for fuel performance and that less zinc will be needed to achieve the desired reactor coolant soluble Co-60 to soluble zinc ratio for dose control [1]. The lower bound of the range was based on limited operating experience with feedwater iron below 0.1 ppb.

The good practice value of < 0.05 ppb for feedwater copper is mainly to minimize the potential for CILC (crud induced localized corrosion) fuel failures. Minimizing copper transport to the reactor also has radiation dose control and IGSCC mitigation benefits [1].

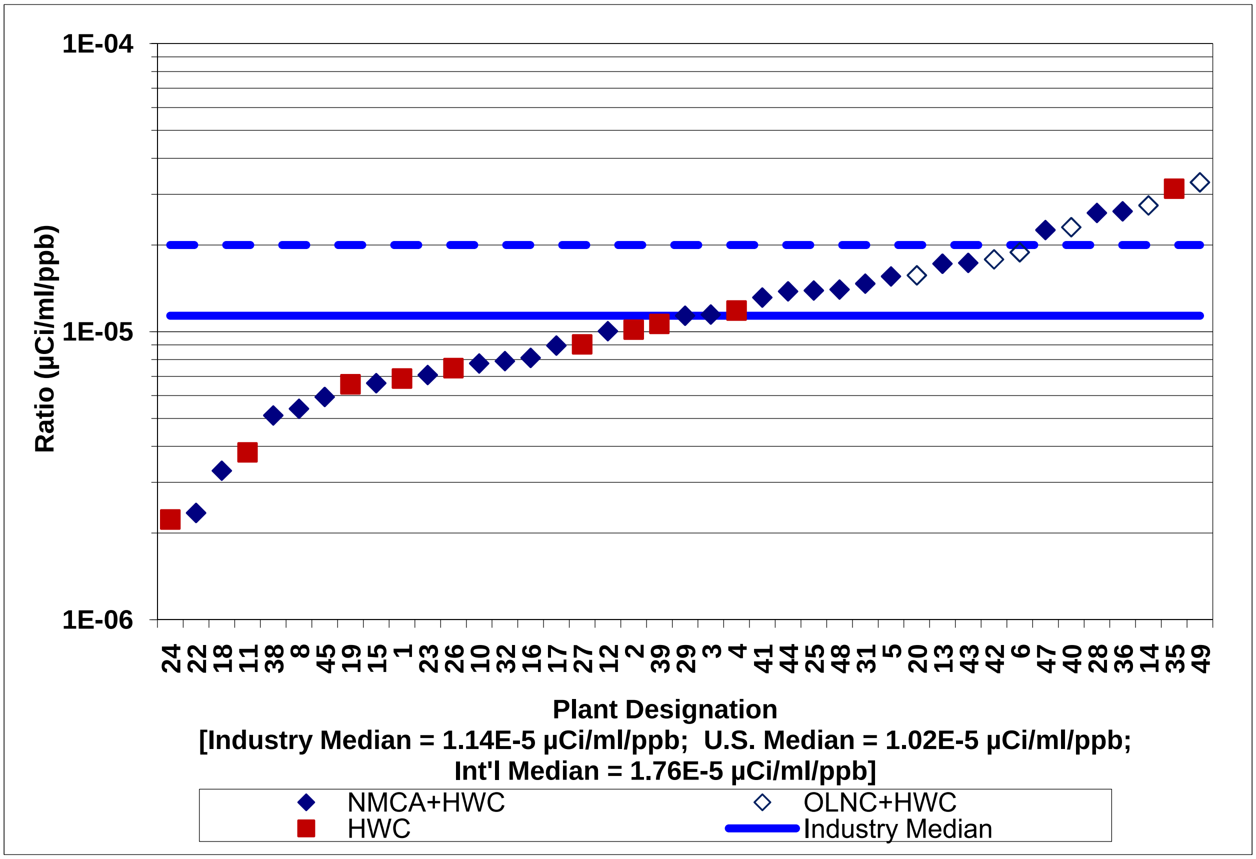

Figure 3 Median Reactor Water Soluble Co-60/ Zinc Ratio (2010)

5. COBALT SOURCE TERM

Elemental cobalt (Co-59) is present in a number of components in the BWR. Typical steam-power conversion systems (main and extraction steam, main turbine, feedwater, condensate, and heater drains) include a number of valves that have Stellite trim/overlay on seating surfaces. Stellite materials typically contain between 50 and 60% Co-59 by weight. Stellite hard faced components, and certain reactor internal components, such as BWR control rod blade roller balls and pins, have been identified as primary cobalt sources. Austenitic stainless steels used in the BWR environment typically contain trace amounts of Co-59. As these materials wear, they contribute Co-59 to the water. When Co-59 enters the reactor coolant, it may become activated to produce Co-60, which is the primary source of gamma radiation dose to BWR workers. Extended BWR operation will continue to result in wear and erosion of plant materials and the ongoing input of elemental cobalt into the reactor vessel unless cobalt sources are removed by replacement with materials that contain much lower or no cobalt.

A methodology of categorizing BWRs with respect to cobalt source term has been developed [4]. The attributes of monitored plants that fall into the low and high cobalt source term categories were summarized, as shown in Table 2 [5]. The pertinent attributes include specific values or ranges for parameters and plant design features.

Attributes of Low and High Cobalt Source Term BWRs

Attribute	Low Source Term	High Source Term
CRE	Best quartile performance (low CRE)	Worst quartile performance (high CRE)
BRAC	< 100 mR/hr	> 200 mR/hr
Total Co-60	< 1E-4 μCi/ml	> 2E-4 μCi/ml
Gamma Scan	Co-60 deposition < 5 $\mu g/cm^2$	Co-60 deposition > 10 $\mu g/cm^2$
Cobalt Reduction	≤ 20% OEM CRBs remaining. Stellite® removed from main turbine and major valves downstream of CDE	≥ 60% OEM CRBs remaining. Stellite® in main turbine and in major valves downstream of CDE
Condensate Treatment System Type	Filter + Deep Bed	Deep Bed Only
Heater Drain Design	Cascaded	Forward Pumped

The EPRI BWR Chemistry Monitoring Database contains plant information on Stellite source term for many plants. Data include the original Stellite surface area, the number of original CRBs (control rod blades) with Stellite pins and rollers, Stellite component replacement, and the number of original CRBs that have been replaced with non- Stellite materials.

Some plants had no CRBs with Stellite pins and rollers from the time commercial operation began. A number of plants have eliminated all original design CRBs with Stellite pins and rollers. Some plants have eliminated Stellite from main turbine components.

For example, one BWR-4 has replaced 110 of 137 CRBs as well as a 58 valves with non- Stellite materials since commercial operation began in 1975. The plant has only deep beds in the condensate system, so the removal efficiency of cobalt from the condensate is significantly lower than plants with filters upstream of deep beds. Despite this challenge, this plant has low reactor coolant Co-60 levels, indicating that cobalt source term reduction through replacement CRBs and valves, and turbine upgrades, has been effective.

At a site with two BWR-3s, main turbine components containing Stellite were replaced with non- Stellite materials within the past five years. Recirculation system chemical decontaminations were performed at each unit in 2004 and 2005. Historically, dose rates at both units would increase significantly after recirculation system chemical decontaminations that were performed at the end of nearly every operating cycle. Replacement of the main turbine components has abated this trend, and BRAC dose rates at these BWRs are now among the lowest in the fleet.

At dual unit site with BWR-4s that that began commercial operation in the mid-1980s , about 70% of the original CRBs have been replaced with blades that have non-Stellite pins and rollers. Both units have cascaded drains with condensate filters upstream of deep bed demineralizers and have low reactor coolant Co-60 levels and low reactor recirculation piping dose rates.

Industry cycle median Co-60 values versus the percent of original CRBs remaining are shown in Figure 4. The data of one monitored BWR unit are not included in the plot because elevated Co-60 levels resulting from jet pump wedge wear skew the results.

While the linear regression correlation coefficient is low, it can be seen that most plants with less than 30% OEM CRBs remaining have total Co-60 concentrations ≤ 2E-4 µCi/ml, while most plants with greater than 50% OEM CRBs remaining have Co-60 concentrations ≥ 2.4E-4 µCi/ml.

A comparison of plants of similar design can help quantify the effect of the cobalt source term from CRBs on reactor coolant Co-60. Two BWR-5s with forward pumped heater drains, pre-filters and deep bed demineralizers in the condensate system, and until recently, admiralty brass condenser tubes are noted in Figure 4. Unit 2 never had OEM CRBs with Stellite, while Unit 1 has a high percentage of OEM CRBs remaining. The median Co-60 concentrations at Unit 1 are about a factor of two higher than at Unit 2.

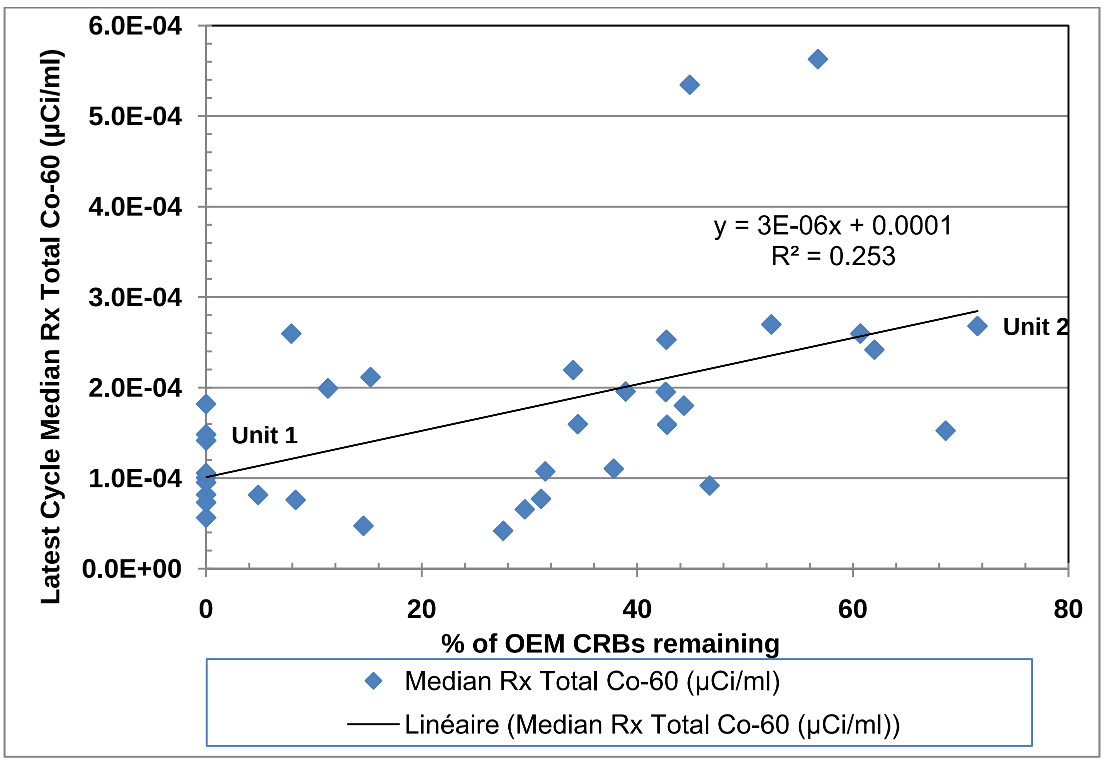

Figure 4. Median Reactor Water Total Co-60 vs. Percent of OEM Control Rod Blades Remaining

6. RADIATION FIELD CONTROL EXPERIENCE

The BWR fixed point survey program, commonly referred to as BRAC (BWR Radiation Level Assessment and Control), established a consistent set of fixed survey points in order to monitor radiation buildup, review plant operational and design factors for effect on dose rates, and to provide reference data input to radiation buildup modeling. The BRAC values are the average of the recirculation pumps' suction and discharge contact dose rate readings taken in the vertical piping runs, usually with a shielded directional probe. The latest reported BRAC point average dose rates for the BWRs participating in the BWR Chemistry Monitoring Program, as of June 2010, are shown in Figure 5. Plants minimize BRAC dose rates through optimized chemistry control and, when necessary, performing chemical decontamination of the reactor recirculation system piping.

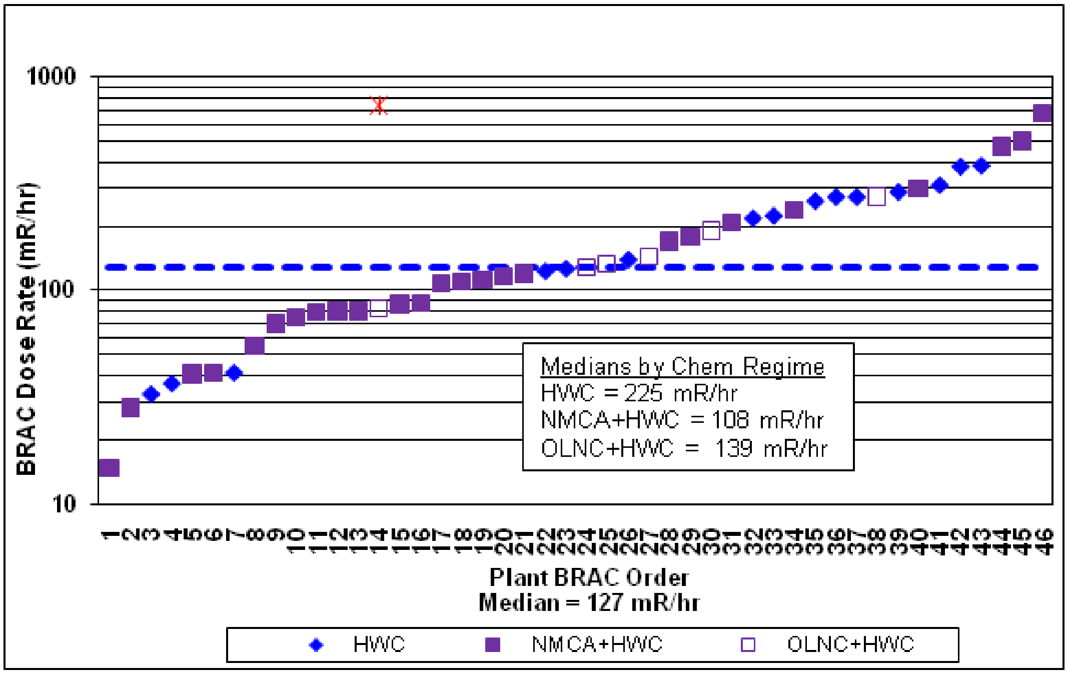

Figure 5. BRAC Dose Rates by Chemistry Regime

Plants perform recirculation piping gamma scans during some, but not all, refueling outages. Gamma scan data were compiled from multiple cycles at 18 BWRs (NWC, HWC, and NMCA/OLNC). BRAC dose rates are plotted in Figure 5 versus the average Co-60 activity measured at the BRAC points. In this plot, the plants are differentiated by chemistry regime; the trend line is for all data points. An excellent linear correlation was found between BRAC dose rates and Co-60 surface activity. The four highest Co-60 activity (and BRAC) values are associated with two BWR-5 design plants and one BWR-6 design plant.

Cobalt source term has an effect on BRAC dose rates. As shown in Figure 7, the plants with the lowest cobalt source term can achieve the lowest BRAC dose rates.

In the past, recirculation system chemical decontaminations (chem decons) were performed during nearly every outage at some BWR stations. While this strategy is an effective means of lowering BRAC dose rates, chem decons are costly and impact outage critical path time. However, when used in conjunction with chemistry program changes and/or source term reduction, they have proven helpful in achieving some plants' long term dose reduction goals. Some plants have achieved and maintained low BRAC dose rates by zinc injection, chemistry regime changes and cobalt source term reduction, without performing chemical decontaminations. BRAC and milestone historical results for one such plant are presented in Figure 8. The campaign of CRB replacements in the 1990s is particularly noted.

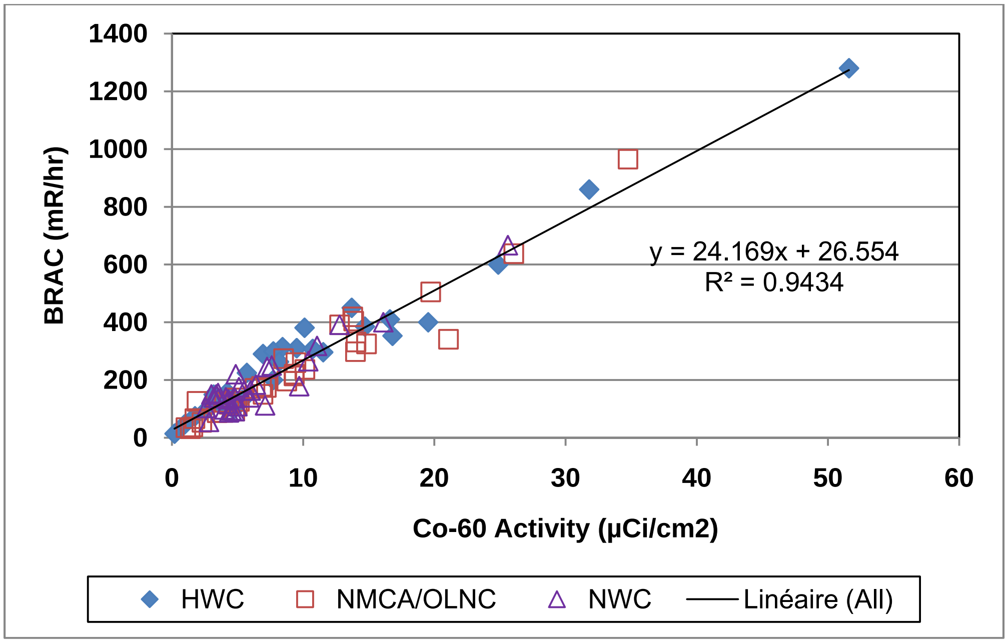

Figure 6. BRAC vs. Recirculation Piping Co-60 Activity (Average at BRAC Points)

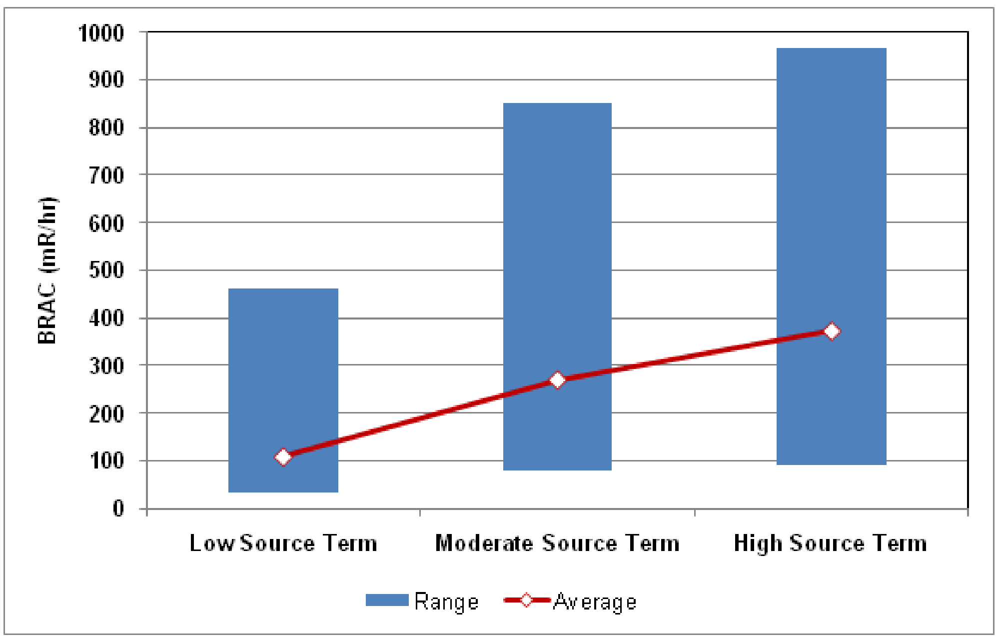

Figure 7. BRAC Dose Rates Grouped by Cobalt Source Term

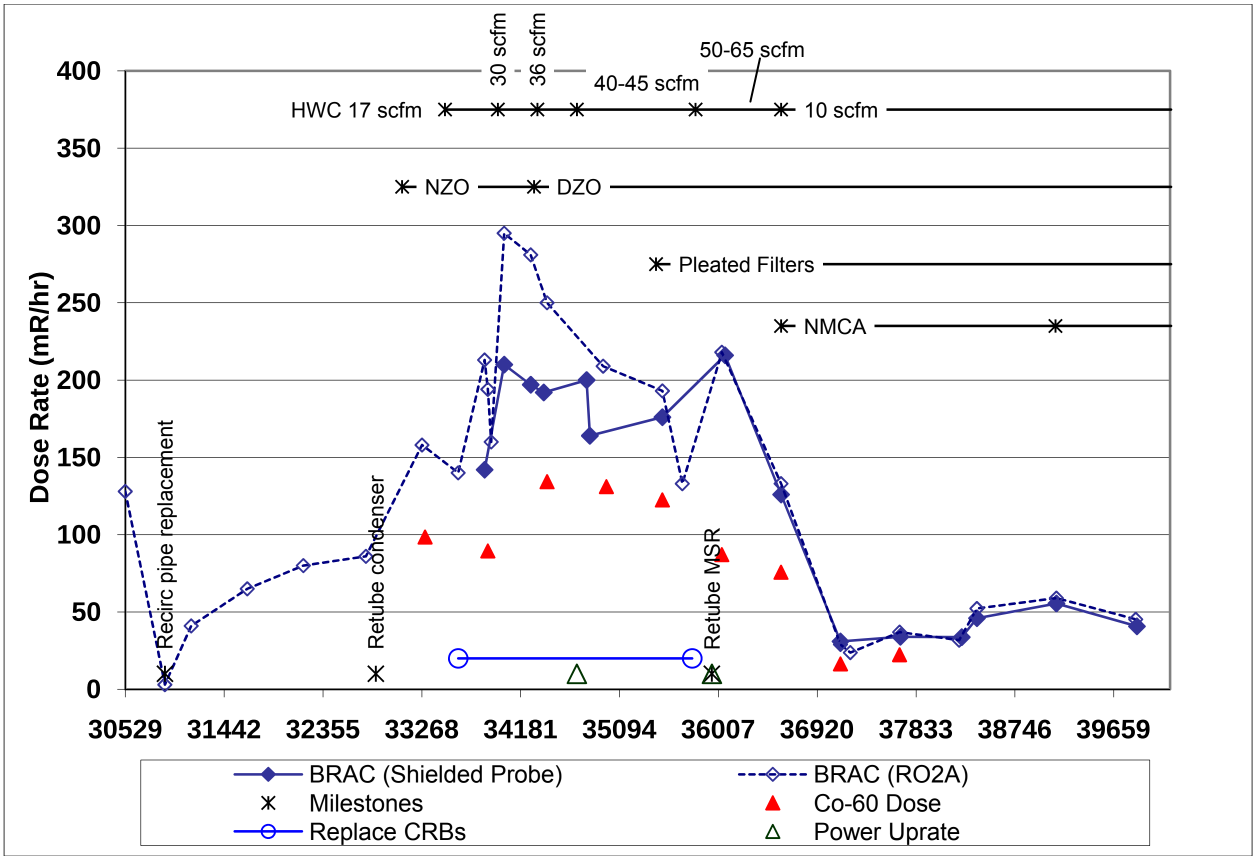

Figure 8. BWR-4 BRAC-Milestone History with Cobalt Source Term Reduction

For NMCA plants, the beneficial effect on BRAC dose rates of controlling the reactor water soluble Co-60/soluble Zn ratio <2E-5 µCi/ml/ppb in the first cycle after an NMCA initial application or reapplication for BWR-2 through BWR-4 plants is shown in Figure 9. Meeting the goal is beneficial during the first two cycles after NMCA, but the benefits are not evident in subsequent cycles after application or reapplication [6]. This suggests that the dose rate reduction experienced with NMCA is diminished after two cycles (48 months for most BWRs). The benefits of soluble Co-60/soluble Zn ratio control on BWR-5 and BWR-6 plants is less evident, and there may be no benefit in increasing feedwater zinc above a cycle average value of 0.4 ppb, recommended for fuel reliability to lower the ratio. The higher recirculation piping velocities in BWR-5/6 plants compared to those in earlier BWR designs may be a factor in the different response.

Early indications of the BRAC dose rate response with OLNC have been favorable, as shown in Figure 10. A decreasing trend after three applications is also shown for a BWR-5, suggesting that OLNC may have a more beneficial effect on dose rates for BWR-5/6 plants than NMCA. Note that the BWR-4 with five OLNC applications operates with 12-month fuel cycles, while the other BWRs shown operate with 24-month fuel cycles.

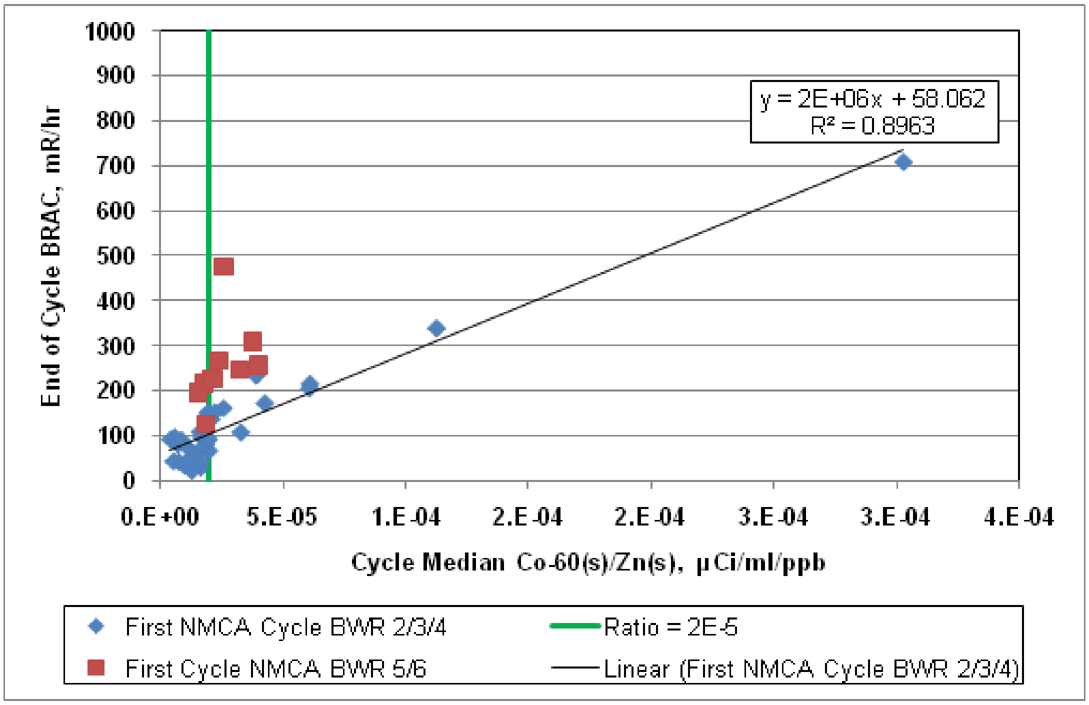

Figure 9. BRAC vs. Cycle Median Reactor Water Co-60(s)/Zn(s) for NMCA Plants (First Cycle after Initial Application or Reapplication)

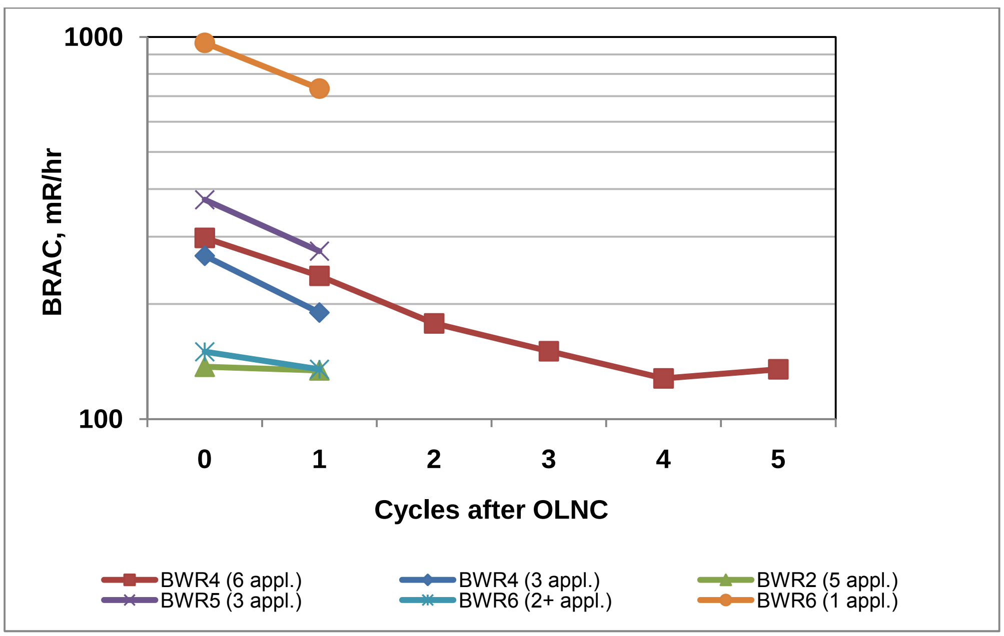

Figure 10. BRAC Dose Rate Response with OLNC

EPRI has a large database of BRAC dose rate history for reporting plants. Recent emphasis has been placed on correlating operational chemistry control with actual radiation dose to workers, and the applicability of BRAC in such correlations has been questioned. As a first step, efforts were made to test for correlations between BRAC dose rates and collective radiation exposure in refueling outage years. Collective radiation exposure data that are reported by U.S. reactors and published in NUREG 713 [7] were used. This annual report is useful in evaluating trends in occupational radiation exposure to assess the effectiveness of licensees' radiation protection programs to maintain exposures as low as reasonably achievable (ALARA). For HWC-M plants, there was an excellent correlation between collective radiation exposure and BRAC (Figure 11). For NMCA plants, there was no general correlation between collective radiation exposure and BRAC. However, for BWRs of Types 2, 3, and 4, CRE tends to be higher at plants with higher BRAC. There is no correlation for BWR 5 or 6 plants with BRAC dose rates less than 400 mR/hr. The plant with significantly higher BRAC than other plants also has the highest CRE.

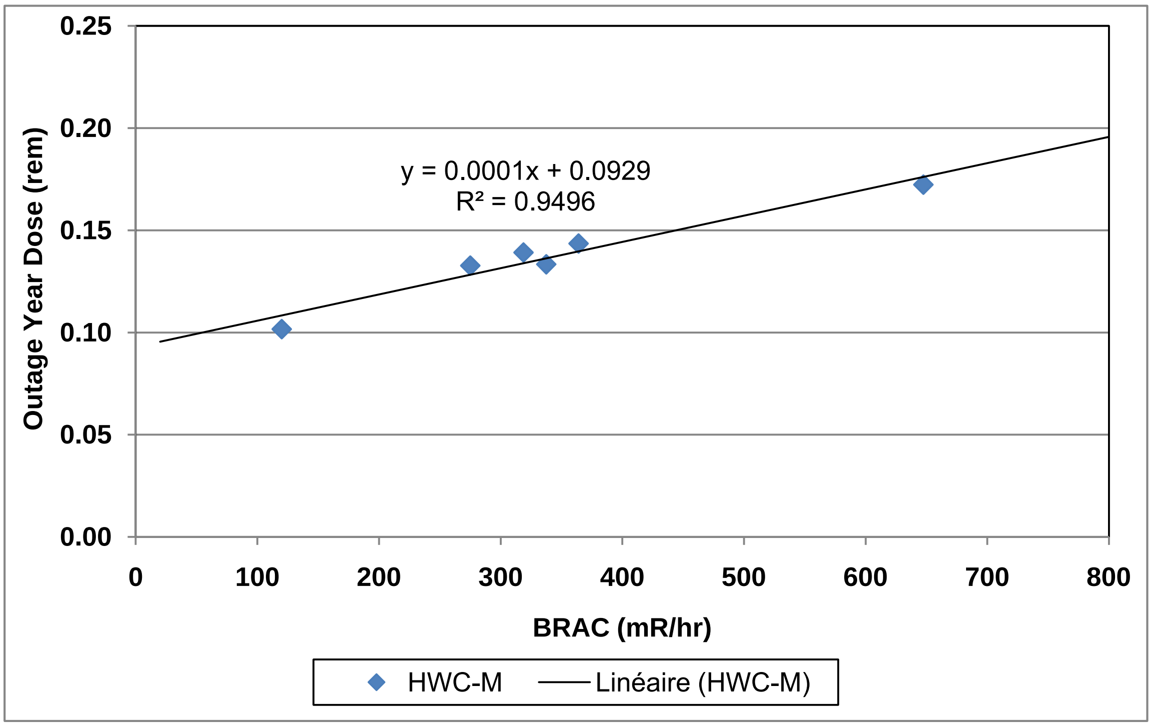

Figure 11. Collective Radiation Exposure vs. BRAC during Refueling Outage Years for HWC Plants

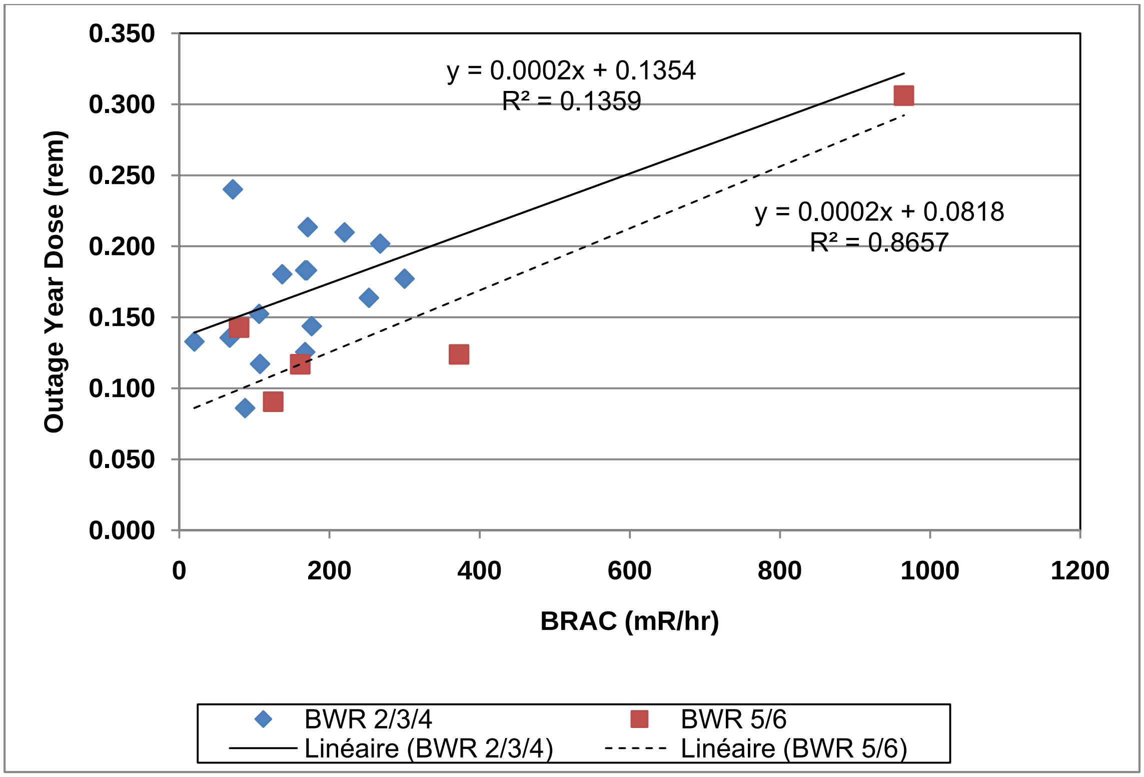

Figure 12. Collective Radiation Exposure vs. BRAC during Refueling Outage Years for NMCA Plants

7. FEEDWATER IRON AND ZINC CONTROL

Progress of monitored BWRs in reducing feedwater iron since 1997 is shown in Figure 13. Since condensate polishing type has a major effect on feedwater iron control, averages in Figure 13 are shown for DB (deep bed), F+DB (filter + deep bed) and FD (filter demineralizer) plants. Annual average feedwater iron by condensate polishing type is also shown in Figure 14 for BWR Water Chemistry Guidelines revision years 2000, 2004 and 2008. The iron reduction progress among plants with filters is mainly attributed to implementation of pleated and hollow fiber condensate filtration technologies. Five of the monitored BWRs currently inject iron to maintain a feedwater concentration >0.1 ppb. Seven U.S. BWRs are now operating with feedwater iron <0.1 ppb, including one plant that has had four refueling outages since low feedwater iron was established. No adverse effects on fuel or Co-60 transport have been attributed to low iron so far.

Fuel crud spallation has been correlated with the feedwater zinc concentration. The Guidelines [1] state that for NMCA plants, the quarterly average feedwater zinc concentration should not exceed 0.5 ppb, and the cycle average should not exceed 0.4 ppb. As shown in Figure 15, the probability of spalling for NMCA plants increases as bundle exposure increases when cycle average feedwater zinc is greater than 0.4 ppb.

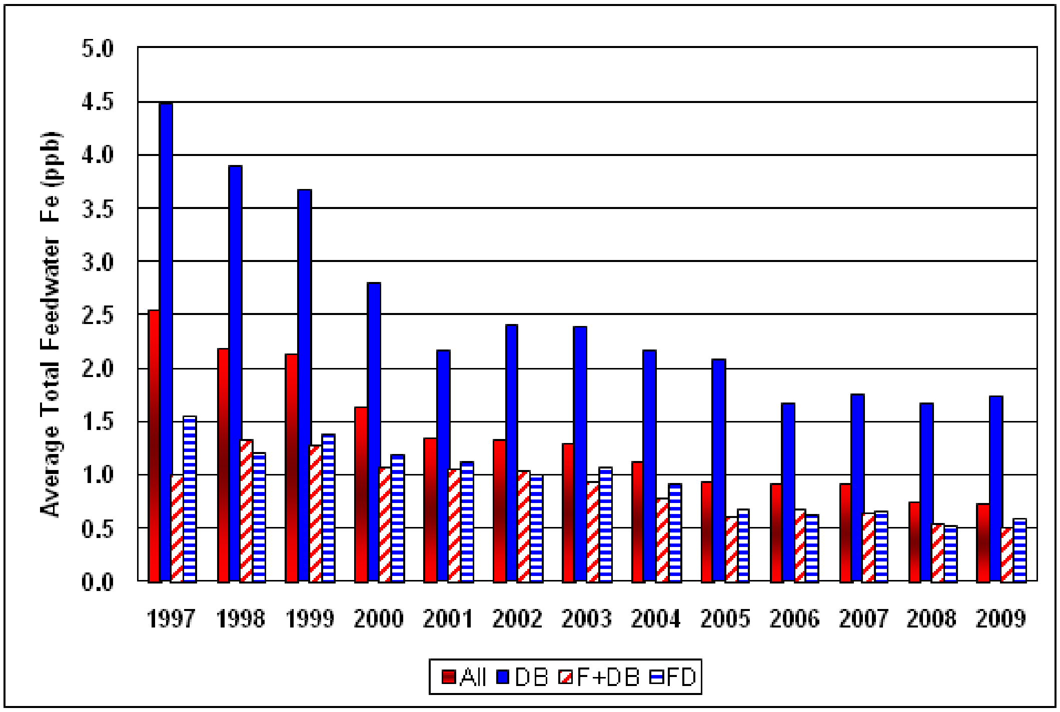

Figure 13. Average Feedwater Iron

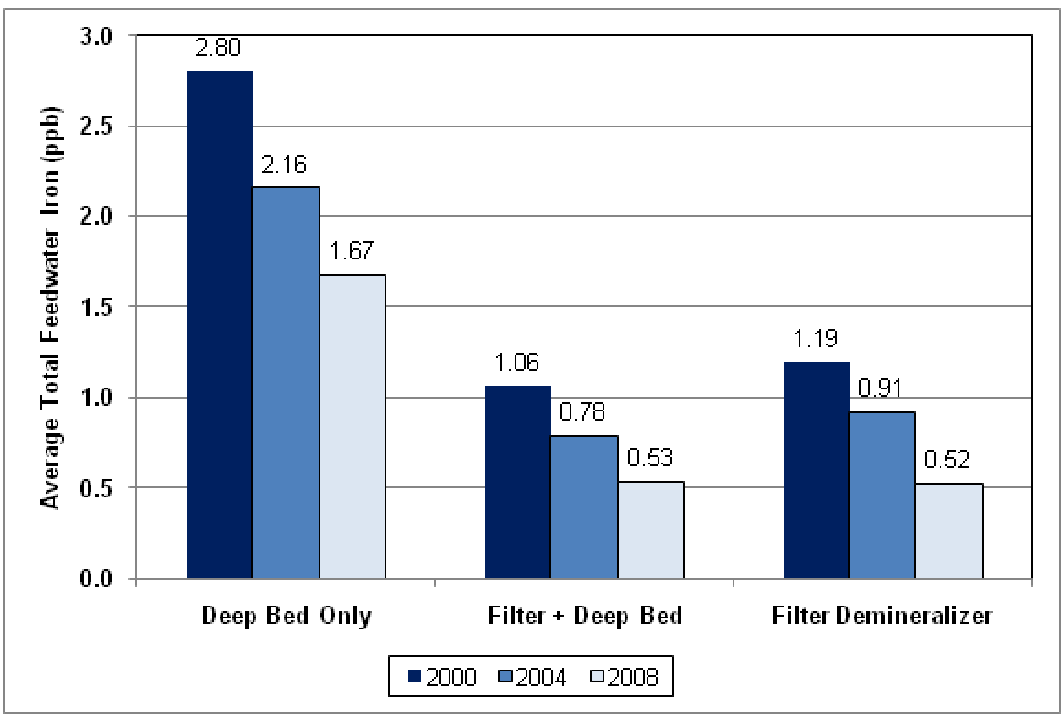

Figure 14. Average Feedwater Iron by Condensate Polishing Type

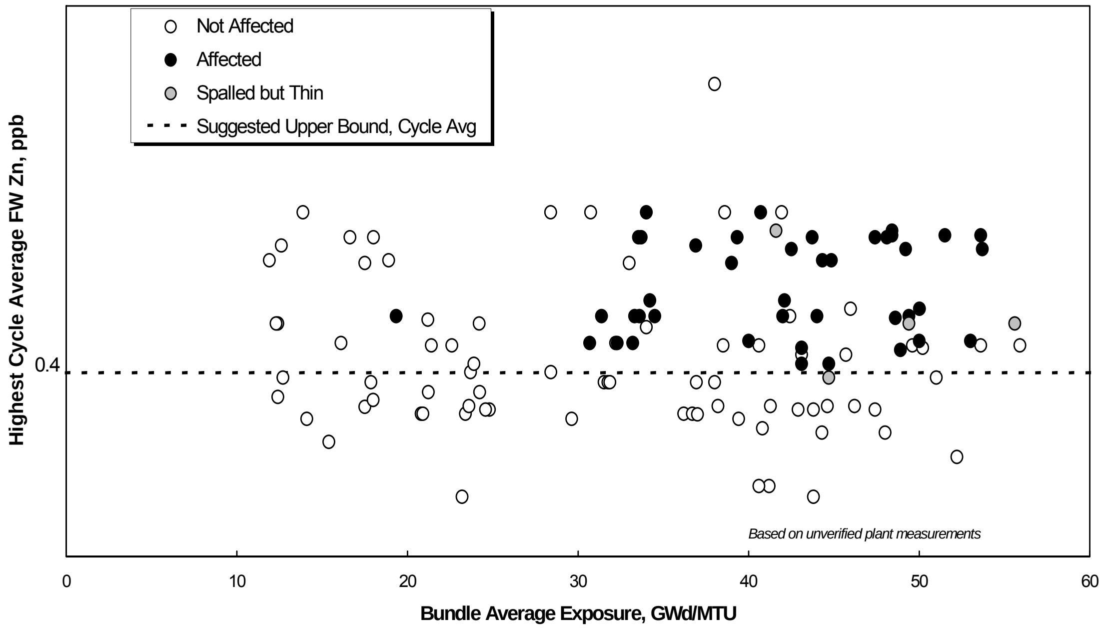

Figure 15. Crud Spalling vs. Cycle Avg. FW Zinc and Bundle Exposure for NMCA Plants

As feedwater iron decreases, lower zinc injection rates are needed to achieve a target reactor water zinc concentration to establish the reactor water soluble Co-60/soluble Zn goal of <2E-5 μCi/ml/ppb for control of shutdown radiation dose rates. Average results and the predicted reactor water zinc concentration for a feedwater zinc concentration of 0.4 ppb are shown in Figure 16. The average zinc concentration factor for the twelve cycles with feedwater iron <0.2 ppb is 31.7 and for the thirteen cycles with feedwater iron >2 ppb, the average zinc concentration factor is 11.7. The U.S. plant with the longest operating time with <0.1 ppb feedwater iron has a reactor water to feedwater zinc concentration factor of approximately 60. Industry results show that the EPRI goal for the Co-60/Zn ratio was met by 92% of plant cycles beginning in 2004 – 2007 without exceeding 0.4 ppb feedwater zinc. This is an improvement compared with 52% for plant cycles beginning in 2000 – 2003.

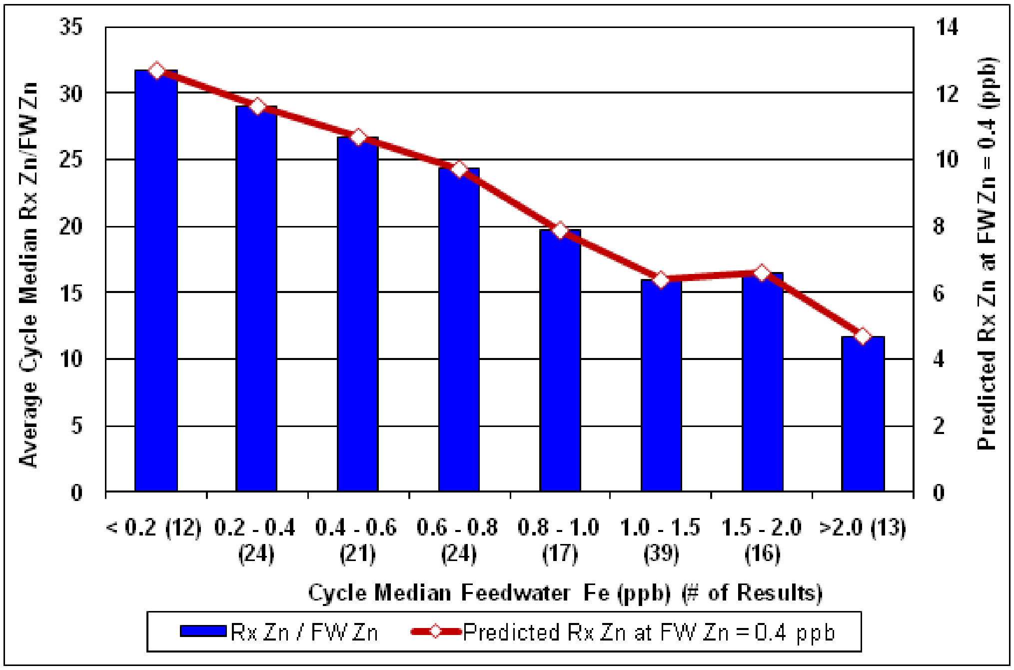

Figure 16. Reactor Water/Feedwater Zinc Concentration Factor vs. Feedwater Iron

8. FUEL CRUD DEPOSITS

As feedwater iron is lowered, iron available for deposition on the fuel decreases. Since cobalt activation to Co-60 occurs primarily when cobalt is deposited with iron on the fuel surface, the implications of lower iron deposition on Co-60 production were investigated.

Crud deposits on BWR fuel are found in two layers: a loose outer layer and tight inner layer. Crud samples are collected by brushing, which removes the loose outer layer, and scraping, which removes the tight inner layer. Sample results that have been consolidated in the EPRI BWR Fuel Crud Database were evaluated to determine the relationship between cobalt and Co-60 in the deposit and the amount of deposited iron.

Deposited cobalt versus deposited iron for both brushed and scraped results presented in Figure 17 show a linear correlation for both the brushed and scraped samples. The ratio of Co/Fe in the scraped samples is higher than that in the brushed samples, as indicated by the greater slope of the linear trend line. Similar results were found by Japanese investigators [8]. Co-60 deposit measurements extracted from the EPRI Fuel Crud Database are plotted in Figure 18. The quantity of Co-60 in the fuel deposit is found to increase with the amount of iron deposited for both the brushed and scraped samples. These results indicate that by lowering the mass of crud deposited on the fuel, less Co-60 is generated in the deposit. Iron mass balance results for BWR cycles with high feedwater high iron (1.5 – 3 ppb) show average iron deposition on fuel surfaces of 1000 – 3000 $\mu g/cm^2$. For low iron cycles, the average deposition is less than 200 $\mu g/cm^2$. The amount of deposited cobalt and Co-60 in both brushed and scraped layers is expected to become very low as the reactor vessel iron inventory decreases and the amount of deposited iron becomes small. For plants that have transitioned from high to low feedwater iron, it may take several cycles before the iron inventory is reduced to very low values due to iron redistribution from old to new fuel surfaces.

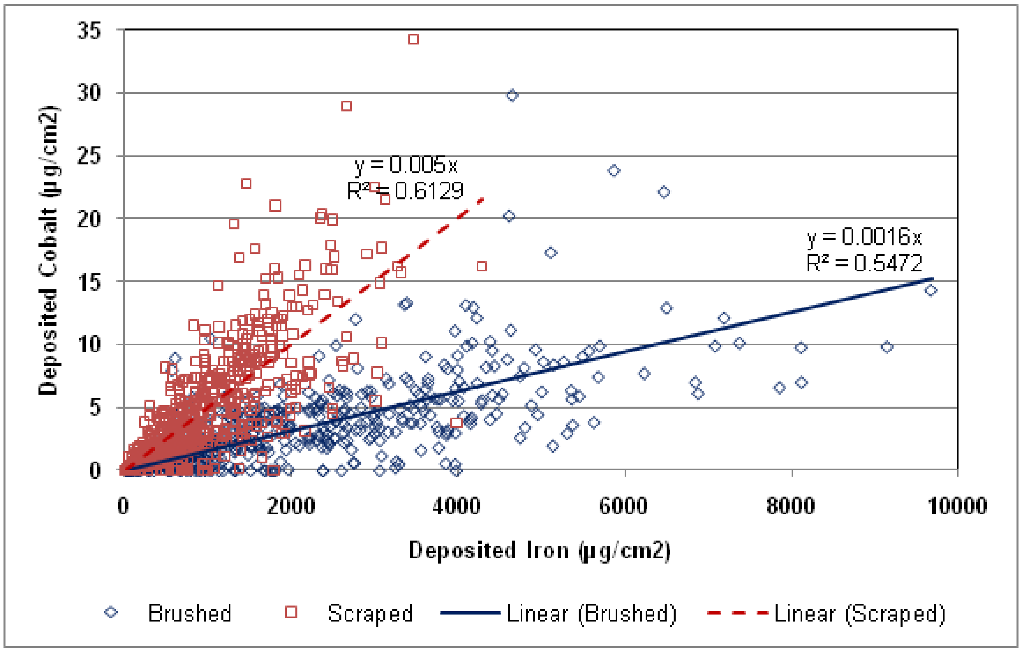

Figure 17. Cobalt and Iron in Brushed and Scraped Fuel Deposits

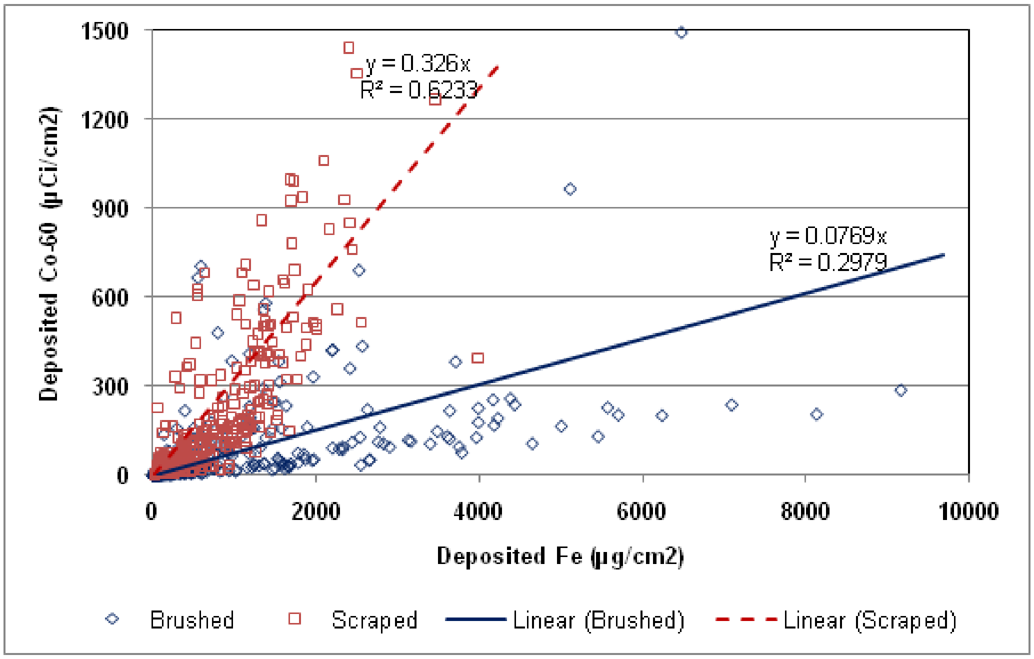

Figure 18. Cobalt-60 vs. Iron in Brushed and Scraped Fuel Deposits

9. CONCLUSIONS

The EPRI Boiling Water Reactor (BWR) Water Chemistry Guidelines were revised in 2008, focusing on operational chemistry control for IGSCC mitigation, fuel reliability and radiation field reduction. Most of the EPRI-monitored BWRs have performed NMCA and the transition to OLNC is projected to continue over the next few years. BRAC dose rates are effectively controlled at most plants following NMCA by maintaining the soluble Co-60/soluble Zn ratio <2E-5 μCi/ml/ppb, although the benefit is less after the second NMCA cycle for BWR 2/3/4 and at any time for BWR 5/6 plants. OLNC experience so far shows decreasing BRAC dose rates as the annual applications continue. Plants that have significantly reduced cobalt sources in combination with optimizing operational chemistry have been successful in maintaining low BRAC dose rates, which correlate with low Co-60 surface activity on the reactor recirculation piping. Initial results indicate some correlation between low BRAC dose rates and low collective radiation exposure during refueling outage years. As feedwater iron decreases, most plants are managing the Co-60/Zn ratio without exceeding feedwater zinc concentrations at which fuel crud spallation becomes more probable, thus improving fuel reliability. Fuel crud samples show that lower deposited iron corresponds with lower deposited cobalt and Co-60 in both the loose outer layer and tight inner layer of deposits. Therefore, continued operation with low feedwater iron is expected to result in less Co-60 production and improved radiation field control.

10. REFERENCES

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