

Boiling Water Reactor Chemistry Performance Monitoring Report—2009 Edition

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EPRI Project Manager
S. Garcia

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CITATIONS

This report was prepared by

Finetech, Inc.
959 Route 46E, Suite 403
Parsippany, NJ 07054

Principal Investigators

J. Giannelli
M. Jarvis
A. Jarvis
D. Morgan

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REPORT SUMMARY

Successful operation of a nuclear power plant demands careful monitoring of water chemistry, particularly in boiling water reactors where control of iron and copper in the reactor coolant is essential. Optimum operation of condensate polishers is key to controlling these and other metal species. Since the advent of hydrogen water chemistry (HWC), other chemistry regimes such as noble metal chemical application (NMCA) and zinc injection have been successfully applied to control radiation fields and provide additional mitigation for intergranular stress corrosion cracking (IGSCC). A variation of NMCA, On-Line NobleChem™ (OLNC), also has been implemented at several plants. This report compiles recent boiling water reactor (BWR) plant experience with these various chemistries and reviews comparative performance and properties of the three types of BWR condensate polishing systems.

Background

BWR water chemistry has evolved from essentially pure, relatively oxidizing water to the current programs, which include hydrogen addition for IGSCC mitigation, depleted zinc oxide (DZO) addition to minimize shutdown dose rates, and NMCA/OLNC to minimize main steam operating dose rates. *BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines—2008 Revision* (1016579, 2008) provides recommendations and guidelines for such programs. Additional information may be found in other EPRI publications, including *BWRVIP-159: BWR Vessel and Internals Project: HWC/ NMCA Experience Report and NMCA Applications Guidelines* (1013397, November 2006) and *BWRVIP-225: BWR Shutdown and Startup Chemistry Experience and Application Sourcebook*, (1019072, to be published in 2009). This report represents the status, as of September 2009, of chemistry programs and issues impacting performance of the thirty-seven North American, five European, and four Taiwanese BWRs that participate in the EPRI BWR Chemistry Monitoring and Assessment effort.

Objectives

To compile and summarize chemistry data and shutdown radiation field results for the forty-six BWRs that participate in the BWR Chemistry Monitoring and Assessment effort and to update information published in *Boiling Water Reactor Chemistry Performance Monitoring Update—2007 Edition* (1016102, December 2007).

Approach

As part of the ongoing BWR Chemistry Monitoring and Assessment effort, EPRI gathers information on plant design, operating practices, chemistry control, IGSCC mitigation and monitoring strategies along with chemistry and dose rate data. Information, data, correlations, and summaries of actual BWR chemistry performance, experiences, and practices will provide useful inputs to the 2010 interim review of the EPRI *BWR Water Chemistry Guidelines—2008*

Revision. This project is jointly funded by the EPRI Water Chemistry, BWR Vessel and Internals Project (BWRVIP) Mitigation, and Fuel Reliability programs.

Results

All forty-six participating BWRs currently inject hydrogen into feedwater to mitigate IGSCC. The majority of these plants also have implemented NMCA and/or OLNK to decrease the hydrogen concentration required to mitigate IGSCC and to minimize increases in main steam line dose rates. In addition, most plants add zinc oxide that is depleted in the ^{64}Zn isotope (DZO) for shutdown radiation field minimization.

Control of iron and copper corrosion products in the final feedwater is highly dependent on the type of condensate polishing system in use and, in some cases, whether drains are pumped forward or cascaded to the main condenser. Consequently, this report examines performance of deep bed demineralizers, filter demineralizers, and prefilter/deep bed combinations. Deep bed demineralizers with upstream prefilters afford the best removal of both particulate and soluble materials, combining the excellent solids removal of prefilters with the superior ion exchange performance of deep beds, without the need to clean deep bed resins.

The chemistry and radiation dose database and information on operating and monitoring strategies included in this report offer significant value to plant operators for process optimization and benchmarking. Periodic electronic reports provide updates and disseminate the most current water chemistry information at least annually to EPRI member stations.

EPRI Perspective

Chemistry data presented in this report influence IGSCC mitigation, radiation dose control, flow-assisted corrosion control, and fuel reliability. At present, this report provides the most comprehensive database available for BWR water chemistry operations and radiation trends. It will be the principal source document for developing plant operating strategies and for interim review of the *BWR Water Chemistry Guidelines*.

Keywords

BWR

BWR chemistry monitoring

IGSCC

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First Energy	Perry
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LIST OF ACRONYMS

AA	Atomic Adsorption Spectroscopy
AL	Action Level
ALARA	As Low as Reasonably Achievable
ARCS	Advanced Resin Cleaning System
BRAC	BWR Radiation Level Assessment and Control
BWR	Boiling Water Reactor
BWRVIA	BWR Vessel and Internals Application
BWRVIP	BWR Vessel and Internals Project
C/A	Cation to Anion
CDE	Condensate Demineralizer Effluent
CDI	Condensate Demineralizer Inlet
CE	Capillary Electrophoresis
CEI	Chemistry Effectiveness Indicator
CF/D	Condensate Filter Demineralizer
CILC	Crud Induced Localized Corrosion
CORD-UV	Chemical Oxidation Reduction Decontamination - Ultraviolet
CP	Condensate Polisher, Condensate Polishing
CPD	Condensate Pump Discharge
CST	Condensate Storage Tank
DB	Deep Bed Demineralizer
DG	Graver DualGuard™
DH	Dissolved Hydrogen
DO	Dissolved Oxygen
dP	Differential Pressure
DZO	Depleted Zinc Oxide
ECP	Electrochemical Corrosion Potential
EHWC	Early Hydrogen Water Chemistry
EOC	End of Cycle
EPRI	Electric Power Research Institute
EPU	Extended Power Uprate

F+DB	Filter + Deep Bed
FAC	Flow-Assisted Corrosion, Flow-Accelerated Corrosion
FCV	Flow Control Valve
F/D	Filter/Demineralizer
GE	General Electric
GEH	GE-Hitachi
HFF	Hollow Fiber Filter
HWC	Hydrogen Water Chemistry
HWC-L	Low Hydrogen Water Chemistry
HWC-M	Moderate Hydrogen Water Chemistry
IC	Ion Chromatography
ICP	Inductively-Coupled Plasma
IFD	Integrated Flow Distributor
IGSCC	Intergranular Stress Corrosion Cracking
INPO	Institute of Nuclear Power Operations
LLD	Lower Limit of Detection
LOMI	Low Oxidation-State Metal Ion
LTNC	Low Temperature NobleChem™
MCO	Moisture Carryover
MMS	Mitigation Monitoring System
MPI	Mitigation Performance Indicator
MS	Mass Spectroscopy
MSLRM	Main Steam Line Radiation Monitor
NEI	Nuclear Energy Institute
NM	Noble Metal(s)
NMCA	Noble Metal Chemical Application
NMCA+HWC	Noble Metal Chemical Application and Hydrogen Water Chemistry
NP	Nitric Permanganate
NRC	Nuclear Regulatory Commission
NRHX	Non-Regenerative Heat Exchanger
NWC	Normal Water Chemistry
NZO	Natural Zinc Oxide
OLNC	On-line NobleChem™
PCI	Pellet-Cladding Interaction
PI	Performance Indicator
PLC	Programmable Logic Controller
PWR	Pressurized Water Reactor

RFO	Refuel Outage, Refueling Outage
RHX	Regenerative Heat Exchanger
RPV	Reactor Pressure Vessel
RWCU	Reactor Water Cleanup
SAC	Strongly Acidic Cation
SBA	Strongly Basic Anion
SCC	Stress Corrosion Cracking
SHE	Standard Hydrogen Electrode
SIL	Services Information Letter
URC	Ultrasonic Resin Cleaner
UV	Ultraviolet Light
WAC	Weakly Acidic Cation
XRF	X-ray Fluorescence
ZCF	Zinc Concentration Factor (Reactor Water Zinc/Feedwater Zinc)

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1

INTRODUCTION

The purpose of this report is to update available chemistry and radiation dose control data for thirty-seven North American, five European, and four Asian BWR (Boiling Water Reactor) plants. This work draws on plant data that are continually collected and maintained in the EPRI BWR Chemistry Monitoring database. This database is maintained to support several EPRI initiatives in the Chemistry, BWRVIP, Radiation Management and Fuel Reliability areas. The database has been used as a resource for numerous reports, including the following examples of reports that have been published since 2007:

- BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision (1016579, 2008)
- Fuel Reliability Guidelines: BWR Fuel Cladding Corrosion and Crud (1015451, April 2008)
- BWR Source Term Reduction – Estimating Cobalt Transport to the Reactor (1018371, November 2008)
- BWRVIP-225: BWR Vessel and Internals Project, BWR Shutdown and Startup Chemistry Experience and Application Sourcebook (1019072, to be published in 2009)

The database also supports the EPRI Condensate Filter Users Group and is used to provide direct assistance on individual utility or plant-specific issues.

This report provides an update of the status of chemistry control programs and issues impacting performance. The report documents actual BWR plant chemistry performance, operating experiences and practices relative to the EPRI BWR Water Chemistry Guidelines – 2008 Revision [1]. It is also intended for use as a reference for compiling issues to be considered in the 2010 interim review of the BWR Water Chemistry Guidelines.

Focus areas of the report include: updates to plant chemistry regimes; feedwater iron and copper control status; fuel reliability concerns; radiation field control; noble metals impacts; sampling practices; mitigation monitoring; condensate filtration and deep bed demineralizer status; RWCU design summary and system issues; and implementation of revised water chemistry guidelines.

EPRI BWR Chemistry Monitoring Database

The database encompasses condensate, feedwater and reactor water chemistry data, radiation dose data, plant design data, resins and filters in use, and other data on plant chemistry practices for the thirty-seven operating North American BWRs, five European, and four Asian BWRs listed in Table 1-1. Since the 2005 report was issued, one U.S. BWR has restarted, and two European and four Asian BWRs have been added to the database.

**Table 1-1
Participating BWRs**

BWR	Unit(s)	Utility	Location
Browns Ferry	1, 2, 3	TVA	U.S.
Brunswick	1, 2	Progress Energy	U.S.
Chinshan	1, 2	Taipower	Taiwan
Clinton	1	Exelon	U.S.
Cofrentes	1	Iberdrola	Spain
Columbia	1	Energy Northwest	U.S.
Cooper	1	NPPD	U.S.
Dresden	2, 3	Exelon	U.S.
Duane Arnold	1	FPL	U.S.
Fermi	2	DTE Energy	U.S.
Grand Gulf	1	Entergy	U.S.
Hatch	1, 2	SNOC	U.S.
Hope Creek	1	PSEG	U.S.
James A. FitzPatrick	1	Entergy	U.S.
Kuosheng	1, 2	Taipower	Taiwan
Laguna Verde	1, 2	CFE	Mexico
LaSalle	1, 2	Exelon	U.S.
Leibstadt	1	Kernkraftwerk Leibstadt	Switzerland
Limerick	1, 2	Exelon	U.S.
Monticello	1	Xcel Energy	U.S.
Mühleberg	1	BKW FMB Energy	Switzerland
Nine Mile Point	1, 2	Constellation	U.S.
Oyster Creek	1	Exelon	U.S.
Peach Bottom	2, 3	Exelon	U.S.
Perry	1	First Energy	U.S.
Pilgrim	1	Entergy	U.S.
Quad Cities	1, 2	Exelon	U.S.
Ringhals	1	Vattenfall	Sweden
River Bend	1	Entergy	U.S.
Santa Maria de Garoña	1	Nuclenor	Spain
Susquehanna	1, 2	PPL Susquehanna	U.S.
Vermont Yankee	1	Entergy	U.S.

A depiction of the information collected is provided in Figure 1-1, and a listing of the chemistry data requested is shown in Table 1-2. One key objective of this effort is to reduce burden on plant personnel by minimizing duplicate requests for data. In addition, the reliability of the data is maximized through data quality verification and consistency checks.

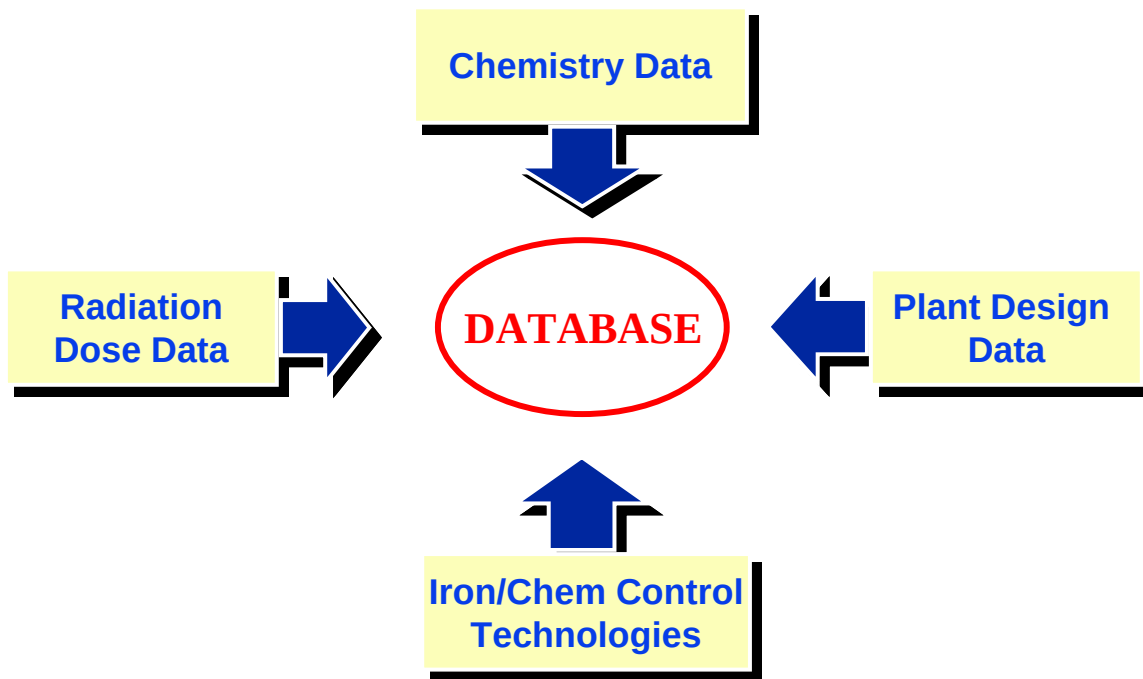


Figure 1-1
Information collected for the EPRI BWR chemistry monitoring effort

Table 1-2
Requested chemistry data

System	Parameters	Comments
Reactor Water	Conductivity, dissolved oxygen, anions, cations, boron, silica, metals, activated corrosion products; iodines	Soluble and insoluble metals and activated corrosion products
Feedwater	Conductivity, dissolved oxygen, dissolved hydrogen, hydrogen flow rate, metals	Soluble and insoluble metals
Forward Pumped Drains (if applicable)	Metals	Soluble and insoluble metals
Hotwell (CDI) and CDE	Conductivity, dissolved oxygen, iron, copper, cobalt	Soluble and insoluble metals
Other	Power, ECP, MSLRM, offgas sum of six, RWCU flow rates, moisture carryover	MCO new in 2009

Electronic Reports

In an effort to report back to plants on a regular basis, the following electronically transmitted reports have been developed. The electronic reports are intended for use by the plant staff in benchmarking and improvement initiatives, and are transmitted annually to corporate and plant representatives for all EPRI member stations which participate in the database. FA listing of the reports is presented in Table 1-3.

Table 1-3
EPRI BWR chemistry monitoring electronic reports

Report Title	Contents	Next Issue
BWR Shutdown Chemistry and Dose Summary (formerly BRAC Summary)	Drywell radiation dose rates and additional parameters that affect outage radiation exposure and activity control	3Q2010
BWR Chemistry Summary	Annual medians for reactor water, feedwater, and condensate chemistry parameters	4Q2009
BWR Deep Bed Resins Report	Resin usage and properties	1Q2010
BWR Mitigation Summary	Status of IGSCC mitigation performance	1Q2010
BWR Precoat Materials Report	Precoat materials usage, dosage, and properties	1Q2010
BWR Sampling Summary	Sampling/analysis frequencies and methodologies	1Q2010

Individual Plant and Utility Assistance

Since issuing the last report, EPRI BWR Chemistry Monitoring and Assessment assistance has been provided to the utilities and stations listed below:

- Constellation Nuclear – Nine Mile Point
- DTE Energy – Fermi
- Energy Northwest – Columbia
- Entergy – Corporate, FitzPatrick, Grand Gulf, Pilgrim, River Bend, Vermont Yankee
- Exelon – Corporate, Clinton, Dresden, LaSalle, Limerick, Oyster Creek, Peach Bottom, Quad Cities
- First Energy – Perry
- FPL – Duane Arnold
- Iberdrola – Cofrentes
- Kernkraftwerk Leibstadt – Leibstadt
- Nebraska Public Power District – Cooper
- Nuclenor – Santa Maria de Garoña

- PPL Susquehanna – Susquehanna
- Progress Energy – Brunswick
- PSEG LLC – Hope Creek
- Southern Nuclear Operating Company – Hatch
- Taipower – Corporate, Chinshan, Kuosheng
- TVA – Browns Ferry
- Xcel Entergy – Monticello

A representative selection of topics grouped by broad category follows. When appropriate, information may be added to electronic reports based on information requests from individual stations.

Chemistry Issues

- Provide chemistry trend data and graphs for use by plants for assessments and benchmarking
- Feedwater iron control, including low feedwater iron guidance and need for iron injection
- RWCU performance issues and resin selection
- Reactor water chloride and sulfate excursions
- Increased reactor water cobalt-60: cause and potential effect on dose
- Condensate demineralizer deep bed and filter management practices
- Chemistry response after implementation of NMCA or HWC
- Performance of cobalt removal resins

Dose Issues

- Dose response after NMCA
- Recontamination after recirculation system chemical decontamination
- Drywell radiation dose rates vs. cobalt-60 concentrations

IGSCC Mitigation

- Provide benchmarking information (HWC availability)
- ECP response during coastdown
- Mitigation during single loop operation

Monitoring/Sampling Issues

- Feedwater metals sampling methods
- Condenser air inleakage detection
- Co-60 sampling methods

References

1. *BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision*. EPRI, Palo Alto, CA: 2008. 1016579.

2

PLANT CHEMISTRY REGIME STATUS

The status of hydrogen injection, zinc addition and application of noble metals at thirty-seven operating North American, five European, and four Asian BWRs is shown in Table 2-1. This table updates the information given in Table 2-6 of the EPRI BWR Water Chemistry Guidelines – 2008 Revision [1]. Data shown are median 2008 (or latest one year) values derived from data provided to the BWR Chemistry Monitoring database.

Hydrogen Water Chemistry (HWC)

The oxidizing chemistry environment of BWR reactor water is the key factor promoting IGSCC (Intergranular Stress Corrosion Cracking) of stainless steel and nickel based alloys used to construct reactor coolant system piping and vessel internals. Work in the early 1980s showed that injecting hydrogen into reactor water would reduce the ECP (electrochemical corrosion potential) of these materials, and thus mitigate IGSCC [1]. Hydrogen addition suppresses the radiolytic decomposition of water in the core region, which reduces the formation of oxidizing species such as oxygen and hydrogen peroxide. Hydrogen addition also provides a large excess of dissolved hydrogen in the downcomer region, which promotes the radiolytic recombination of residual oxidants in the recirculating water. In regions where the concentration of oxidants in reactor water is reduced to <3 ppb (equivalent O_2) the ECP driving force for IGSCC is eliminated. Under NWC (normal water chemistry), the ECP of primary system materials is typically in the range of 0 to +250 mV (SHE). Extensive laboratory and field testing has shown that when the ECP of sensitized stainless steel is lowered to <-230 mV (SHE) and the reactor coolant conductivity is <0.3 $\mu S/cm$ at 25°C, IGSCC of BWR piping is mitigated. Low hydrogen addition (HWC-L), defined as 0.4 - 1.0 ppm hydrogen in the final feedwater, is mainly targeted at protecting the reactor recirculation piping. Moderate hydrogen addition (HWC-M), defined as 1.0 - 2.0 ppm hydrogen in the feedwater, is targeted at protecting reactor internals.

HWC may raise main steam line radiation levels up to six times the level without hydrogen injection. The source of radiation is primarily N-16 (7.1 second half-life) which is produced by the interaction of fast neutrons with O-16 in water. The reducing environment established by HWC causes a larger fraction of the N-16 to be in more volatile chemical forms such as ammonia. This increase in radiation level may preclude the implementation of Moderate-HWC at plants where the following conditions exist:

- Steam-bearing equipment is not well shielded, resulting in unacceptable radiation exposure to operating personnel.
- The site layout is such that direct radiation or skyshine from steam bearing equipment results in unacceptable radiation exposure to site personnel.
- The site location is such that direct radiation or skyshine produces unacceptable radiation levels at the site boundary or areas occupied by the public.

Table 2-1
BWR chemistry regime status

BWR	HWC Start Date	HWC-M Start Date	FFW H2 (ppb) Note 1, Note 2	NZO Start Date	DZO Start Date	RW Zn (ppb) Note 1	Zn System	NMCA Date(s)	LTNC Date(s)	OLNC Date(s)	Noble Metal Coupon Initial Deposition ($\mu\text{g}/\text{cm}^2$)
Browns Ferry 1	7/07		0.25		5/07	12.1	passive	11/07			1.59
Browns Ferry 2	12/99	12/99	0.25		10/97	11.6	passive	3/01 4/09			0.95 0.97
Browns Ferry 3	8/00		0.25		12/95	13.0	passive	4/00			1.03
Brunswick 1	6/90	1/94	1.06		5/95	11.6	passive				n/a
Brunswick 2	1/89	1/94	1.06		3/96	15.0	passive				n/a
Chinshan 1	10/06	2009*	0.48			0.30	n/a				n/a
Chinshan 2	10/06	2009*	0.50			0.34	n/a				n/a
Clinton	7/02		0.27		12/00	8.42	passive	4/02 1/08			0.75 1.66
Cofrentes	3/97	3/97	1.66		7/96	6.65	passive			11/09*	n/a
Columbia	9/04		0.21		9/96	10.8	passive	5/01 5/07			0.51 0.89
Cooper	1/03		0.20		12/99	12.8	passive	3/00 1/05		2010*	0.65 0.79
Dresden 2	4/83	1/87	0.39		12/96	8.82	passive	10/99 10/03			0.80 0.21
Dresden 3	3/99	3/99	0.35		7/98	6.22	passive	10/00 10/06			0.30 1.15
Duane Arnold	7/87		0.25		12/94	11.6	passive	10/96 10/99 3/05		2011*	0.22 0.80 1.45

Table 2-1
BWR chemistry regime status (continued)

BWR	HWC Start Date	HWC-M Start Date	FFW H2 (ppb) Note 1, Note 2	NZO Start Date	DZO Start Date	RW Zn (ppb) Note 1	Zn System	NMCA Date(s)	LTNC Date(s)	OLNC Date(s)	Noble Metal Coupon Initial Deposition ($\mu\text{g}/\text{cm}^2$)
Fermi 2	9/97	9/97	2.20		7/95	7.00	passive			2011**	n/a
FitzPatrick	8/88		0.24	1/89	4/96	7.31	passive	11/99 9/04		2011*	1.18 0.35
Grand Gulf	5/99	4/07	1.88		2/98	4.40	passive			2010*	n/a
Hatch 1	9/87	1/94	0.26	8/90	2/94	7.97	passive	3/99 2/06		2010*	0.70 0.61
Hatch 2	9/91	1/95	0.26	8/90	12/93	7.11	passive	3/00 2/07		2011*	1.30 0.41
Hope Creek	2/93	2/93	0.20	12/86	2/93 Note 3	9.39	active	4/06			1.58
Kuosheng 1	11/06	6/2009	0.51			1.01	n/a				n/a
Kuosheng 2	11/06	6/2009	0.51			0.86	n/a				n/a
Laguna Verde 1	12/05		0.10		6/98	5.68	passive	9/05			1.42
Laguna Verde 2	6/06		0.10		8/98	6.43	passive	4/06			2.03
LaSalle 1	8/99		0.26		7/94	12.3	passive	10/99 2/06			0.70 0.28
LaSalle 2	8/00		0.27		6/95	18.4	passive	11/00 2/07	2/05		1.00 2.33 0.72
Leibstadt	9/08		no data	2/90	9/92	6.15	passive			9/08	Note 4
Limerick 1	9/98		0.20	1992	5/97	15.1	active	3/00 3/08			1.16 0.97
Limerick 2	1/98		0.21	1991	5/97	16.3	active	4/01 3/07			1.12 0.54
Monticello	2/89	1/92	1.61	11/89	4/93	14.8	active			2013*	n/a

Table 2-1
BWR chemistry regime status (continued)

BWR	HWC Start Date	HWC-M Start Date	FFW H2 (ppb) Note 1, Note 2	NZO Start Date	DZO Start Date	RW Zn (ppb) Note 1	Zn System	NMCA Date(s)	LTNC Date(s)	OLNC Date(s)	Noble Metal Coupon Initial Deposition ($\mu\text{g}/\text{cm}^2$)
Mühleberg	11/00		0.18		8/98	5.53	passive	8/00		7/05 1/06, 1/07, 1/08, 1/09	0.87 Note 4
Nine Mile Point 1	4/00		0.25		10/02	9.76	passive	5/00		12/06 1/08, 9/08, 9/09	2.10 Note 4
Nine Mile Point 2	2/01		0.27	4/88	7/99	6.96	passive	9/00		12/07 12/08, 9/09	1.00 Note 4
Oyster Creek	2/92		0.30		7/00	5.72	passive	10/02 11/08			0.32 1.08
Peach Bottom 2	5/97		0.29	6/91	10/96	13.1	passive	10/98 9/06			2.80 1.20
Peach Bottom 3	3/97		0.30	6/92	10/96	11.3	passive	10/99		7/07 4/08, 2/09	0.66 Note 4
Perry	8/02		0.19	2/90	1997	10.2	passive	2/01	4/07 Note 5	11/08 9/09	0.90 4.10 Note 4
Pilgrim	9/91	6/95	0.24		12/96	7.02	passive	4/07		2012*	1.20
Quad Cities 1	9/90	9/90	0.31		9/98	16.9	passive	4/99 5/07	3/05		0.60 1.58 1.73

Table 2-1
BWR chemistry regime status (continued)

BWR	HWC Start Date	HWC-M Start Date	FFW H2 (ppb) Note 1, Note 2	NZO Start Date	DZO Start Date	RW Zn (ppb) Note 1	Zn System	NMCA Date(s)	LTNC Date(s)	OLNC Date(s)	Noble Metal Coupon Initial Deposition ($\mu\text{g}/\text{cm}^2$)
Quad Cities 2	10/90	10/90	0.31		6/97	16.6	passive	1/00 3/06	3/04		2.33 1.89 0.47
Ringhals 1	1982	1984	1.05			<0.1	n/a				n/a
River Bend	12/01	2/03	2.06		6/97 Note 6	10.7	passive			2010*	n/a
Santa Maria de Garoña	6/86	6/86	no data		3/99	4.86	passive				n/a
Susquehanna 1	1/99	1/99	1.97		10/03	7.03	passive				n/a
Susquehanna 2	8/99	8/99	1.97		12/02	6.80	passive				n/a
Vermont Yankee	11/03		0.15		1/09	6.51	passive	4/01 5/07		2012*	1.24 0.63

Table 2-1 Notes

*Planned

**Considering

n/a = not applicable

1. Concentrations shown are medians of latest one year's data.
2. When DH is not provided, values are estimated from H₂ injection rate.
3. No zinc added cycle 6, 6/94 – 11/95.
4. Approx. 10 $\mu\text{g}/\text{cm}^2$ (fuel surface area) injected during each OLNC application.
5. RWCU only.
6. Suspended 6/99 – 7/00.

Hydrogen injection with noble metal application, described below, provides a means of achieving the IGSCC protection of HWC-M without a large increase in main steam line radiation levels.

As of September 2009, all forty-six (46) plants were injecting hydrogen to protect vessel internals and/or reactor recirculation system piping from IGSCC. Of these plants:

- Thirty-one (31) plants had applied noble metals, most after having operated for some time with HWC-M.
- Fifteen (15) plants were operating with moderate hydrogen (HWC-M). Five of these plants are planning or considering future noble metal addition.

Noble Metal Application

Noble metal application involves the deposition of small amounts of materials such as platinum and rhodium on the wetted surfaces in contact with the reactor coolant. These catalyze recombination reactions of hydrogen with oxygen and hydrogen peroxide at those surfaces. The ECP response of the treated surfaces is similar to that of platinum. Protective ECPs are achieved when the molar ratio of hydrogen to total oxidant in reactor water reaches a value equal to or greater than two, which is achieved at low feedwater hydrogen concentrations (usually between 0.1 and 0.3 ppm), about an order of magnitude lower than that required by HWC-M.

There are several noble metal application processes [1]:

- NMCA (Noble Metal Chemical Application, NobleChem™) – Noble metals (platinum and rhodium) are applied at a temperature of 225 – 310°F, just before a plant shutdown, usually for refueling. The process requires about 54 – 58 hours of critical path time to complete. The amount of noble metal injected results in a net fuel loading not to exceed 30 $\mu\text{g}/\text{cm}^2$ per fuel bundle lifetime. Reapplication is recommended every 4 to 4.5 years.
- LTNC (Low Temperature NobleChem™) – Noble metals (platinum and rhodium) are applied to recirculation system piping after a recirculation system chemical decontamination.
- OLNC (On-line NobleChem™) – Noble metal injection (platinum only) is performed when the plant is operating at or near full power. The amount of noble metals injected during each application is equivalent to a fuel loading of about 10 $\mu\text{g}/\text{cm}^2$. Reapplication is recommended every 11 to 16 months.

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 hydrogen addition levels. A disadvantage is that cracking which may initiate or propagate during periods when hydrogen is not available may not be mitigated when hydrogen is restored, although OLNC may reduce this impact by coating fresh crack surfaces with catalytic material during normal operation [1]. When cracks grow beyond a critical length, oxidants in the bulk water may raise the ECP of the fresh crack surfaces above -230 mV (SHE). Plants operating with HWC-NMCA strive for very high hydrogen availabilities ($\geq 98\%$) and for limited hydrogen outages. Early HWC (EHWC) is being evaluated to inject hydrogen during heatup and low power operation during startup before feedwater hydrogen injection is available to minimize crack growth during these periods. Work toward a demonstration of EHWC at Peach Bottom is in progress, targeted for the fall 2010 refueling outage.

Thirty (30) plants had performed NMCA as of September 2009. Of these plants, twenty (20) had implemented HWC prior to NMCA, and six (6) began hydrogen injection within a few months of NMCA. Columbia, Cooper, Perry and Vermont Yankee began hydrogen injection more than one year after NMCA was performed. Two reapplications have been performed at one BWR, and eighteen BWRs have performed one reapplication.

Six BWRs have performed OLNC. Five plants (Mühleberg, Nine Mile Point 1 and 2, Peach Bottom 3, Perry) performed OLNC after having initially performed NMCA and Leibstadt is the first BWR to have performed OLNC as its initial noble metal application. Four OLNC reapplications have been performed at Mühleberg, three at Nine Mile Point 1, two each at Nine Mile Point 2 and Peach Bottom 3, and one at Perry.

Five BWRs are considering or planning OLNC as their initial applications, six BWRs are planning OLNC for their next reapplications, and eleven BWRs are considering OLNC for their next reapplications.

Zinc Addition

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. Initially, NZO (natural zinc oxide) was added to the feedwater, but this had the side effect of increasing Zn-65, produced from the naturally occurring Zn-64 isotope, which added to the radiation field source. This led to the introduction of DZO (depleted zinc oxide), which now contains <1% Zn-64 compared to about 48% in natural zinc oxide; consequently, the production of Zn-65 is significantly reduced.

As of September 2009, forty-one (41) BWRs, including all U.S. BWRs, were adding DZO to the feedwater for drywell radiation field control. Vermont Yankee is the most recent plant to begin DZO injection (January 2009). The Kuosheng units, which do not inject zinc, have a natural zinc source in the copper alloy main condenser tubes that provides a reactor water zinc concentration of about 1 ppb.

Of the forty-one plants adding zinc, all but two have median reactor water zinc concentrations of ≥ 5 ppb. At a current reactor water zinc concentration of <5 ppb, Grand Gulf maintains a Co-60(s)/Zn(s) ratio of $<2E-5$ in accordance with shutdown radiation dose control recommendations in the BWR Water Chemistry Guidelines [1].

Thirty-seven (37) BWRs have passive zinc addition systems and four (4) have active zinc injection systems.

References

1. *BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision*. EPRI, Palo Alto, CA: 2008. 1016579.

3

IRON AND COPPER CONTROL

BWR Water Chemistry Guidelines for Iron and Copper Control

Feedwater iron and copper recommendations in the BWR Water Chemistry Guidelines – 2008 Revision [1] are summarized in Table 3-1. NWC values are not included in Table 3-1 because all monitored BWRs are now injecting hydrogen for IGSCC mitigation.

Table 3-1
BWR water chemistry guidelines for feedwater iron and copper – power operation
(>10% power) [1]

Feedwater Iron	
Action Level 1	>5.0
Goal for Optimization Lower Bound	>0.1
Goal for Optimization Upper Bound	<1.0
Feedwater Copper	
Action Level 1	>0.20
Goal for Optimization	<0.05

The feedwater iron Action Level 1 limit of 5 ppb in the 2008 Revision is unchanged from the 2004 Revision [2], and the feedwater copper Action Level 1 limit of 0.2 ppb is also unchanged. In the 2008 Revision, power-weighting over the sample period is allowed to more accurately account for corrosion product mass transport during low power operation. Additional guidance on feedwater iron, copper and zinc to address fuel reliability concerns is provided in the notes of Table 6-6b of the 2008 Revision [1] and is summarized as follows:

- The quarterly average (power-weighted) feedwater iron concentration should not exceed 3.0 ppb.
- Based on quarterly averages, if feedwater copper is <0.05 ppb, feedwater iron should not exceed 2.0 ppb when feedwater zinc exceeds 0.5 ppb. For plants with feedwater copper >0.05 ppb, feedwater iron should not exceed 2.0 ppb when the sum of quarterly average feedwater copper and quarterly average feedwater zinc exceeds 0.5 ppb.
- 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. For HWC-M plants, the quarterly average feed water zinc concentration should not exceed 0.6 ppb.

- d) The quarterly average feedwater copper concentration should not exceed 0.1 ppb. For HWC-M plants, feedwater copper levels must be controlled to assure that the reactor water copper concentration does not exceed the value that reduces the effectiveness of hydrogen injection.

The goals for feedwater iron and copper optimization in the 2008 Revision are unchanged from the 2004 Revision [2]. The upper bound for feedwater iron optimization of 1.0 ppb is based on limiting the quantity of crud deposited on the fuel. The lower bound of feedwater iron is unchanged, but, recognizing that more plants are operating with feedwater iron concentrations <0.1 ppb, a note was added to Table 6-6b of the 2008 Revision to “inform the organization responsible for Nuclear Fuel performance if long-term operation with >0.1 ppb feedwater iron is adopted” [1].

The goal for feedwater copper optimization is <0.05 ppb. Industry experience shows a lack of crud induced localized corrosion (CILC) type fuel failures in copper plants at this level. Higher feedwater copper can lead to elevated reactor water copper, which can impede the achievement of low ECP values in HWC-M plants, as discussed below, and may also result in higher dose rates.

Reactor water copper is included as a diagnostic parameter for moderate-HWC plants. The basis is that at soluble copper concentrations of 3 ppb and higher, the effectiveness of hydrogen injection in establishing low ECP (electrochemical corrosion potential) for IGSCC mitigation is reduced. For plants that have copper alloy condenser tubes and operate under HWC-M, the recommended reactor water copper concentration is less than 1 ppb to assure that the ECP at stainless steel surfaces is <-230 mV_{SHE}. Although plant ECP results indicate that IGSCC mitigation is achieved at higher reactor water copper levels in NMCA plants, the reactor water copper goal for these plants is also <1 ppb.

Plant Design Factors Impacting Feedwater Iron and Copper Control

The major factors influencing feedwater iron and copper control are:

1. Condensate polishing system design
2. Heater drains system design
3. Main condenser tube materials of construction (for copper control)

The condensate polishing system design has the greatest influence of the three on feedwater corrosion products control. There are three basic types of BWR condensate polishing system designs:

- **Deep Bed Only (DB)** – Deep bed demineralizers employing bead ion exchange resins. This type of design has a high capacity to remove ionic impurities but limited capability to remove particulate impurities (such as iron and copper oxides).
- **Filter + Deep Bed (F+DB)** – Deep bed demineralizers downstream of high-efficiency backwashable filters. These filters are commonly called prefilterers and they are used without precoat materials. In North America, all but one operating prefilter systems currently employ filter septa with pleated filter media. One U.S. plant uses a Hollow Fiber Filter (HFF) system. The Filter + Deep Bed design provides both efficient removal of insoluble crud particles and

high capacity to remove ionic impurities. One BWR currently employs partial filtration. Two BWRs that used a partial headered system (two prefilter vessels processing about 40% of the condensate flow installed upstream of eight deep bed demineralizers) have installed a full flow prefilter installation using pleated filter technology.

- **Filter Demineralizer (F/D)** – Filter Demineralizers employ filter septa (either pleated or wound) that are precoated with filter aid materials made up totally or partially of powdered cation and anion exchange resins. This design provides efficient removal of insoluble crud particles but has only limited capacity to remove ionic impurities. One European BWR uses unprecoated pleated septa in two of five filter demineralizers that process approximately half of the total condensate flow. One BWR with filter demineralizers has standby deep bed demineralizers for use only during a condenser tube leak, when they are placed in service automatically based on hotwell conductivity.

A summary of the current types of condensate polishing system designs for forty-six (46) BWRs is shown in Table 3-1. Of the twenty-seven BWRs with Deep Bed demineralizers, seven currently have only deep beds and twenty have Filters + Deep beds. There are nineteen plants designed with Filter Demineralizers.

Of the nineteen condensate Filter Demineralizer plants, thirteen employ pleated septa in all filter vessels. Three plants use wound septa in all of their filter vessels, and the remaining three plants use a mix of pleated and conventional wound septa. Pleated septa provide more efficient iron removal and allow lower precoat material usage than conventional wound cylindrical septa. Additional information on septa usage is included in Chapter 9.

The most dramatic trend in North American condensate polisher system design has been the conversion of Deep Bed only systems to the Filter + Deep Bed design. The evolution of condensate polisher designs is summarized in Table 3-2. Condensate polisher types are shown by year in Figure 3-1. In 1990, there were only three North American BWRs with Filters + Deep Beds, while there were seventeen Deep Bed Only and sixteen Filter Demineralizer plants. By 1992, after the two Limerick units were converted to Filter + Deep Beds through a retrofit of deep beds, the number of Filter Demineralizer plants was reduced to fourteen, increasing to fifteen with the restart of Browns Ferry 1 in 2007.

Starting in 1997, the number of filter retrofits to North American deep bed plants increased dramatically. By the end of 2001 there were thirteen North American Filter + Deep Bed plants, reducing the number of North American Deep Bed Only plants to nine. Currently, only three North American Deep Bed Only plants remain.

Of the existing Filter + Deep Bed plants, all of the filter systems process 100% of the condensate flow except at Clinton. Clinton has nine deep bed demineralizer vessels and originally installed slaved filters directly upstream of three vessels (one filter dedicated to one demineralizer). After an extended shutdown, Clinton committed to installing three additional filter vessels, which went into service in 2000 and 2001. Clinton therefore remains a partial filtration plant, with prefilters directly upstream of six of nine demineralizer vessels.

Table 3-2
Current condensate polishing types for monitored North American, European, and Asian BWRs

Deep Bed Only (7 BWRs)	Filter + Deep Bed (20 BWRs)	Filter Demineralizer (19 BWRs)
Chinshan 1	Brunswick 1	Browns Ferry 1
Chinshan 2	Brunswick 2	Browns Ferry 2
FitzPatrick	Clinton (Note 1)	Browns Ferry 3
Grand Gulf	Dresden 2	Cofrentes
Kuosheng 1	Dresden 3	Columbia
Kuosheng 2	Hope Creek	Cooper
Pilgrim	Laguna Verde 1	Duane Arnold
	Laguna Verde 2	Fermi 2
	LaSalle 1	Hatch 1
	LaSalle 2	Hatch 2
	Limerick 1	Leibstadt
	Limerick 2	Monticello
	Nine Mile Point 1	Mühleberg
	Nine Mile Point 2	Peach Bottom 2
	Oyster Creek (Note 2)	Peach Bottom 3
	Perry	Quad Cities 1
	River Bend	Quad Cities 2
	Santa Maria de Garoña	Ringhals 1 (Note 3)
	Susquehanna 1	Vermont Yankee
	Susquehanna 2	

Table 3-2 Notes

1. Partial slaved filtration
2. Hollow fiber filtration
3. Standby deep bed demineralizers

Table 3-3
Condensate polishing evolution at North American BWRs

Plant	Current Type			Original Type if Different	Comments
	DB	F+DB	F/D		
Browns Ferry 1			x		One F/D vessel added for extended power uprate.
Browns Ferry 2			x		One F/D vessel added for extended power uprate.
Browns Ferry 3			x		One F/D vessel to be added for extended power uprate.
Brunswick 1		x			Original FDs converted to non-precoat filters. Septa lengths increased for power uprate.
Brunswick 2		x			Original FDs converted to non-precoat filters. Septa lengths increased for power uprate.
Clinton		x		DB	6 of 9 vessels have slaved prefilters added as retrofit
Columbia			x		Septa lengths increased for power uprate.
Cooper			x		
Dresden 2		x		DB	EPRI-ARCS resin cleaner was added as retrofit. Two headered prefilter vessels added as retrofit. Full flow filtration installation completed.
Dresden 3		x		DB	EPRI-ARCS resin cleaner was added as retrofit. Two headered prefilter vessels added as retrofit. Full flow filtration installation completed.
Duane Arnold			x		
Fermi			x		
FitzPatrick	x				
Grand Gulf	x				Original precoat F/Ds are used during startup at low power.
Hatch 1			x		
Hatch 2			x		
Hope Creek		x		DB	Prefilters added as retrofit.
Laguna Verde 1		x		DB	Prefilters added as retrofit.
Laguna Verde 2		x		DB	Prefilters added as retrofit.
LaSalle 1		x		DB	Prefilters added as retrofit.
LaSalle 2		x		DB	Prefilters added as retrofit.
Limerick 1		x		F/D	Deep beds added as retrofit.
Limerick 2		x		F/D	Deep beds added as retrofit.
Monticello			x		
Nine Mile Point 1		x		DB	Prefilters added as retrofit.
Nine Mile Point 2		x		DB	Prefilters added as retrofit.

Table 3-3
Condensate polishing evolution at North American BWRs (continued)

Plant	Current Type			Original Type if Different	Comments
Oyster Creek		x		DB	ORCS resin cleaning method added as retrofit. Prefilters (HFF) added as retrofit.
Peach Bottom 2			x		F/D flow distribution upgraded.
Peach Bottom 3			x		F/D flow distribution upgraded.
Perry		x		F/D	Original F/Ds converted to non-precoat filters.
Pilgrim	x				EPRI TC – Iron Control Improvement.
Quad Cities 1			x		One F/D vessel added for extended power uprate.
Quad Cities 2			x		One F/D vessel added for extended power uprate.
River Bend		x		DB	Prefilters added as retrofit.
Susquehanna 1		x		DB	Prefilters added as retrofit.
Susquehanna 2		x		DB	Prefilters added as retrofit.
Vermont Yankee			x		Septa diameter increased and F/D flow distribution improved for extended power uprate.

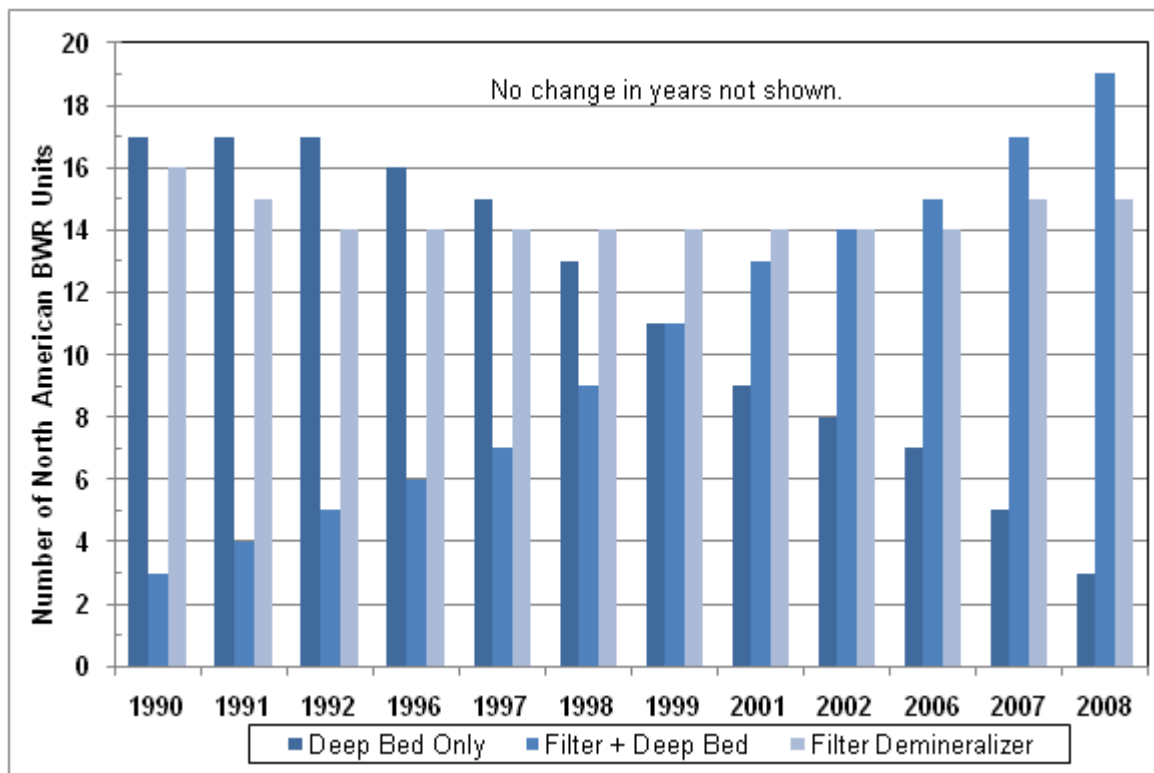


Figure 3-1
Design evolution of North American BWRs

Feedwater Iron Control

The bases for controlling feedwater iron concentrations are given in the EPRI BWR Water Chemistry Guidelines – 2008 Revision [1] and can be summarized as follows:

1. Prevent excessive crud buildup on the fuel that can contribute to fuel failures.
2. Minimize Co-60 transport and corresponding radiation dose rates.
3. Optimize the use of depleted zinc by injecting enough to suppress radiation field buildup while limiting zinc to minimize the risk of fuel crud spallation, which may be a precursor to crud-related fuel failures.

BWR Industry Iron Control Performance

The EPRI BWR Chemistry Guidelines has established a cycle-average goal of 0.1 - 1.0 ppb for feedwater iron. Measures taken by the industry to improve iron control have been successful. This is evident in the downward trend in the 2000 - 2008 average feedwater iron results for North American BWRs shown in Figure 3-2.

Results are shown for all plants for which sufficient data were available to determine a reliable average. Each of the average iron values shown in Figure 3-2 is the simple average of the total iron (soluble and insoluble) reported by each plant at power operating conditions (>10% power). The average may differ from the time-weighted calculations made by plants. In some cases, especially for plants operating with low feedwater iron, cycle median data are used in place of average data.

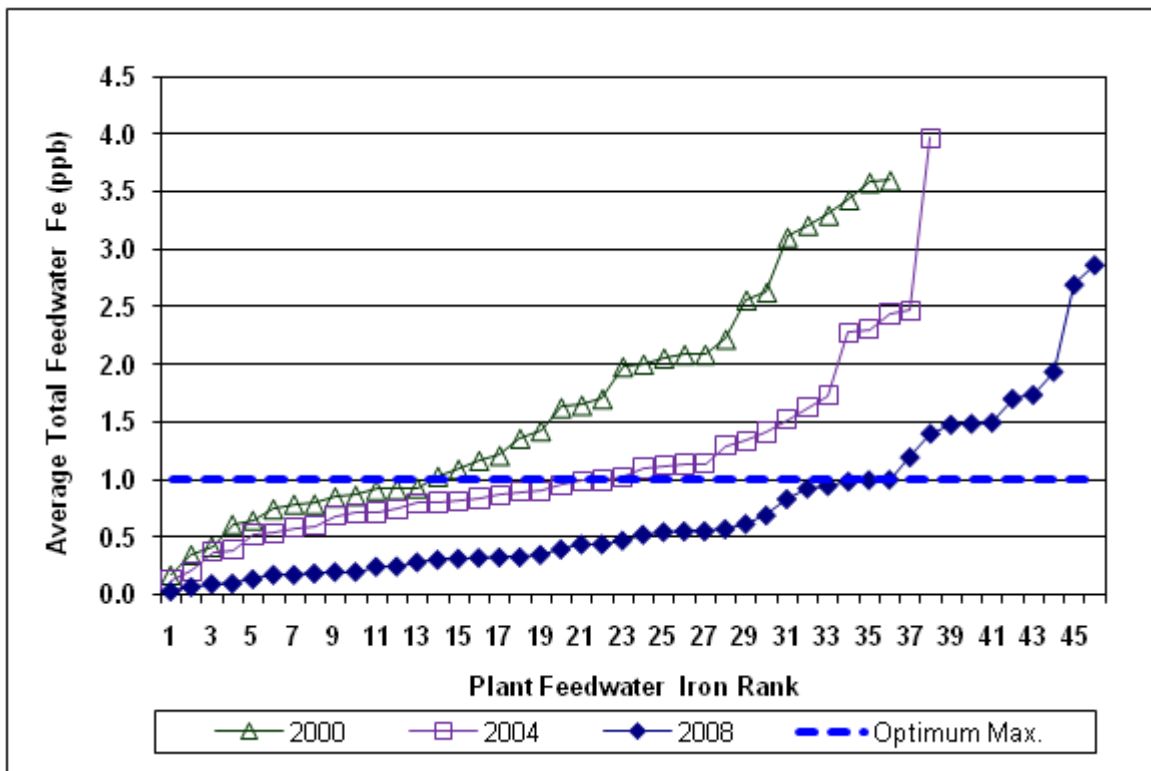


Figure 3-2
2000 – 2008 average BWR feedwater iron

The individual annual average feedwater iron results for 2008 are shown in Figure 3-3. Of the forty-six BWRs for which data are available, thirty-two plants had annual averages in the desired 0.1 – 1.0 ppb range. Four plants had annual averages less than 0.1 ppb, while ten plants had averages greater than the desired range. Only two BWRs had annual averages greater than 2 ppb.

Six of the ten plants having average iron above 1.0 ppb are Deep Bed Only plants. Full flow filtration became operational at Dresden 3 and Nine Mile Point in 2008, so these plants are included in the Deep Bed Only category. Clinton operates with partial flow filtration, and feedwater iron at the Laguna Verde units is influenced by contributions from the forward pumped heater drains. Replacement of feedwater heaters at LaSalle 1 has resulted in lower feedwater iron than at Unit 2, where the heaters continue to be a significant contributor to feedwater iron. At Cofrentes, yarn wound septa are used in all the CF/Ds, and the forward pumped drains also provide iron input to the feedwater.

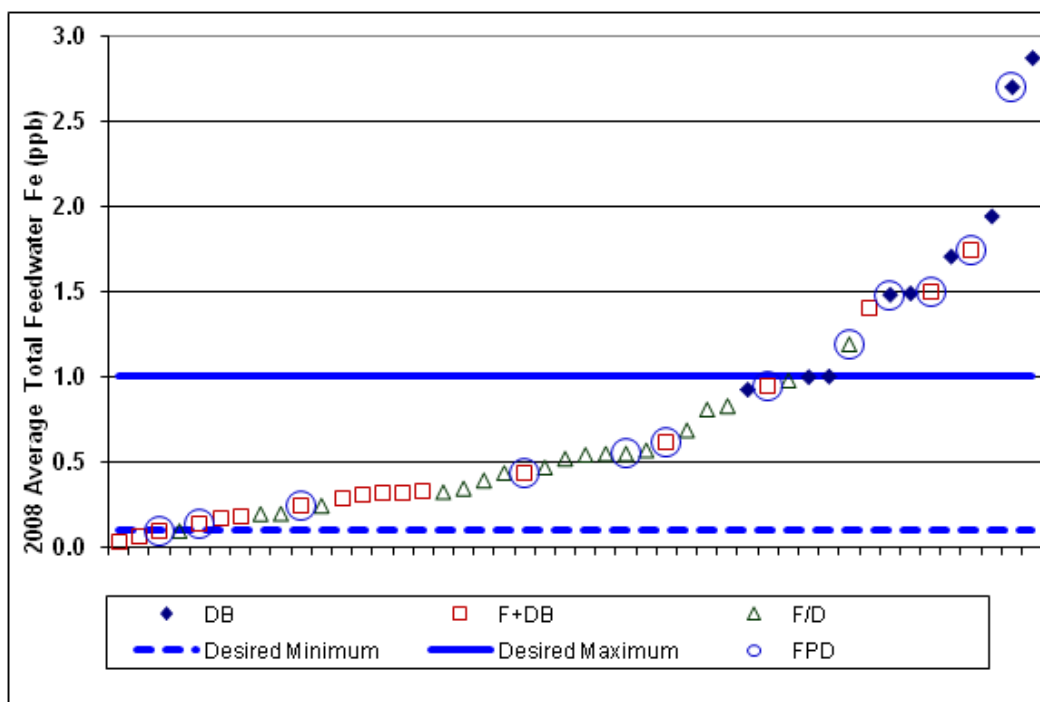


Figure 3-3
2008 average BWR feedwater total iron

Currently, Hope Creek, Limerick 1 and 2, Santa Maria de Garoña, and Susquehanna 1 and 2 are adding iron to the feedwater, but at lower rates than in past years. Columbia has discontinued iron injection. River Bend has the capability to inject iron, but has not implemented feedwater iron injection after condensate prefilter retrofit in 2002. Nine Mile Point 1 is the lead U.S. BWR with cascaded drains to operate with prefilters and without iron injection.

Average feedwater iron concentrations as a function of condensate polisher design type are shown in Figure 3-4 for the years 2000, 2004, and 2008. In all years, the group with the highest average feedwater iron concentration employs Deep Bed Only condensate polishing (this category includes Dresden with partial headered filtration). The Filter Demineralizer plants have

achieved the next lowest average concentrations, while the Filter + Deep Bed plants have the lowest average feedwater iron. At some Filter + Deep Bed plants, despite very low iron concentrations (typically less than 0.1 ppb) in the condensate polishing system effluent, the average feedwater iron concentrations shown in Figure 3-4 are higher due to either iron injection or a significant iron contribution from forward pumped drains. All categories have shown a reduction in feedwater iron since 2000:

- Deep Bed Only – 40% reduction, influenced mainly by prefilter retrofits at previously high feedwater iron plants
- Filter + Deep Bed – 52% reduction, influenced by prefilters operating with no iron injection or reduced iron injection rates and, at LaSalle 1, reduced iron source in the forward pumped drains after feedwater heater replacement
- Filter Demineralizer – 55% reduction, influenced by greater use of high efficiency condensate filter septa and of septa with lower particle retention ratings.

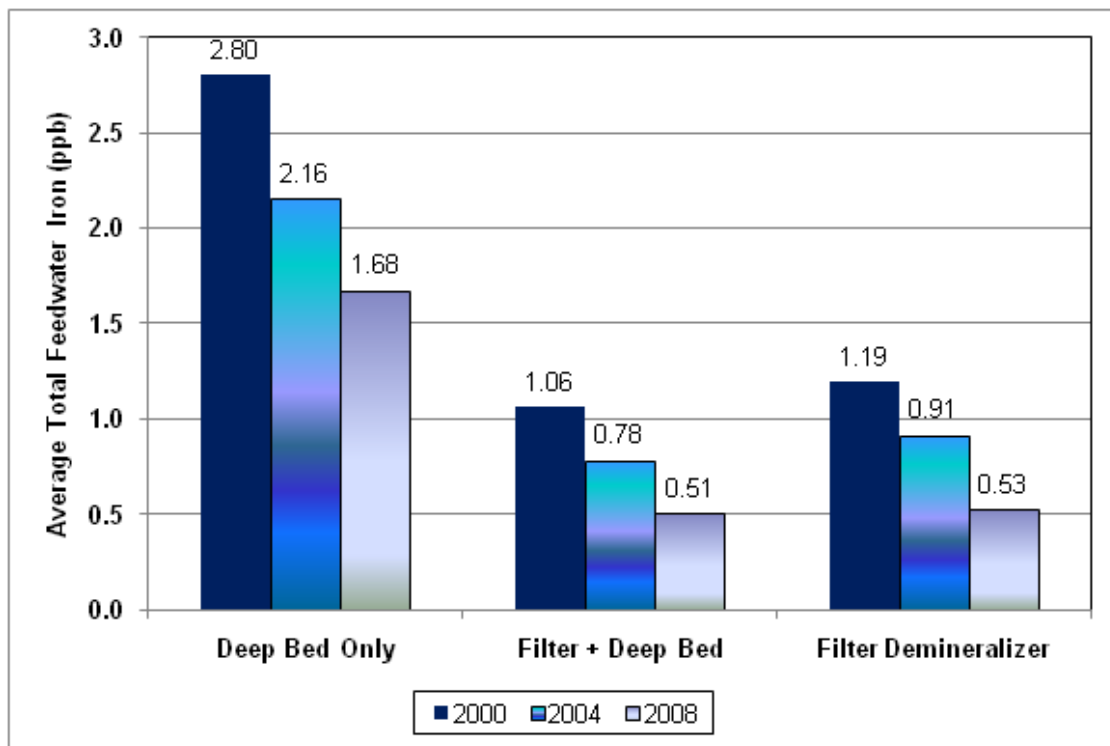


Figure 3-4
2000 – 2008 average feedwater iron vs. condensate polishing type

Impact of Drains Path on Iron Control

In plants with cascaded drains, 100% of the drains flow is returned to the main condenser and processed through the condensate polishing system. In plants with forward pumped drains, approximately 30% of the drains stream is pumped forward into the final feedwater, with the remaining 70% returned to the condenser and processed through the condensate polishing system. (Perry, Leibstadt, and the Laguna Verde units were designed with variations of the

typical forward pumped design.) Plants with forward pumped drains can have a significant iron input to the final feedwater from this source. However, materials of construction must be taken into account to fully assess the impact of drains path on iron control. For plants with all drains cascaded to the hotwell, the iron transported to the feedwater system is equal to the iron contribution from the condensate polishing system effluent (including iron injection if used) plus the net iron transport from the feedwater piping. For plants with forward pumped high pressure drains, the forward pumped drains may contribute significant iron to the final feedwater, depending on the materials of construction of the piping in the flow path.

In general, plants constructed predominantly of carbon steel in the extraction stream, moisture separator drains and high pressure heater drain piping have the highest contribution of iron from the forward pumped drains stream [3]. The Laguna Verde and LaSalle units are examples of plants with mostly carbon steel construction in the forward pumped drains flow path and, despite having full flow condensate filters upstream of deep bed demineralizers, do not achieve feedwater concentrations which are as low as those for plants with cascaded drains. At LaSalle 1, significant feedwater iron reduction from greater than 1 to less than 0.1 ppb was achieved after the #13 feedwater heaters were replaced in early 2008.

Iron Injection

Plants that are routinely injecting iron into the feedwater are shown in Table 3-4; all are Filter + Deep Bed Plants with cascaded drains. Three of these units inject iron in the insoluble hematite form, Fe_2O_3 , and three inject iron oxalate hexahydrate, $\text{Fe}_2(\text{C}_2\text{O}_4)_3 \bullet 6\text{H}_2\text{O}$, which is soluble in the feed tank. The iron oxalate hydrolyzes when it is diluted in the feedwater stream, going to the insoluble iron oxide form. The oxalic acid byproduct produces a measurable increase in feedwater specific conductance; for example, the feedwater specific conductance at Susquehanna is typically $\sim 0.07 \mu\text{S}/\text{cm}$ due to the formation of oxalic acid after injection. Average feedwater iron concentrations for these plants are shown in Table 3-3. All plants currently injecting iron have decreased their iron injection rates.

Columbia and Mühleberg, Filter Demineralizer plants with cascaded drains, have discontinued iron oxalate injection. At River Bend, full flow condensate filters went online in the fourth quarter of 2002, and iron oxalate injection has not been implemented (River Bend has <0.5 ppb iron in the forward pumped drains stream).

Plants with recent prefilter retrofits (Dresden 2 and 3, Nine Mile Point 1 and 2, Oyster Creek) and LaSalle 1, after feedwater heater replacement, continue to monitor data trends to determine whether iron injection is needed. These plants are unlikely to be true low iron plants for at least three cycles after beginning full-flow filtration until all fuel exposed to high feedwater iron has been removed from the core.

Table 3-4
BWRs currently injecting iron into the feedwater

Plant	Condensate Polishing Type	Type of Iron Injected	Feedwater Iron Concentration (ppb)		
			Without Fe Addition	After Fe Addition (2006 Average)	After Fe Addition (2008 Average)
Hope Creek	F + DB	Iron Oxide	<0.1	0.3	0.2
Limerick 1	F + DB	Iron Oxide	~0.2	0.7	0.3
Limerick 2	F + DB	Iron Oxide	~0.2	0.7	0.3
Santa Maria de Garoña	F + DB	Iron Oxalate	<0.1	0.3	0.3
Susquehanna 1	F + DB	Iron Oxalate	<0.1	0.4	0.3
Susquehanna 2	F + DB	Iron Oxalate	<0.1	0.3	0.3

Impact of Feedwater Iron on Feedwater Zinc Injection

As feedwater iron decreases, a lower rate of zinc injection is needed to achieve a target zinc concentration in the reactor water, thus making it easier to achieve the target reactor water Co-60(s)/Zn(s) ratio of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ for control of shutdown radiation dose rates. The lower zinc feed required to maintain a target reactor water zinc concentration can be seen by the trend of the reactor water zinc to feedwater zinc concentration ratio (zinc concentration factor) with feedwater iron in Figure 3-5. The data represent the several most recently completed cycles for plants on HWC-M or NMCA+HWC, with zinc injection. Average results are shown in Figure 3-6, which also shows the predicted reactor water zinc concentration, for a feedwater zinc concentration of 0.4 ppb, using the average ratios for each feedwater iron concentration range. As shown in Figure 3-6, the ability of plants to achieve a desired reactor water zinc concentration without exceeding the 0.4 ppb feedwater zinc concentration recommended in the EPRI BWR Water Chemistry Guidelines – 2008 Revision [1] is limited at higher feedwater iron concentrations. For example, 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. A feedwater zinc concentration 2.7 times higher would be required at plants with feedwater iron >2 ppb compared with plants with feedwater iron <0.2 ppb to achieve the same reactor water concentration.

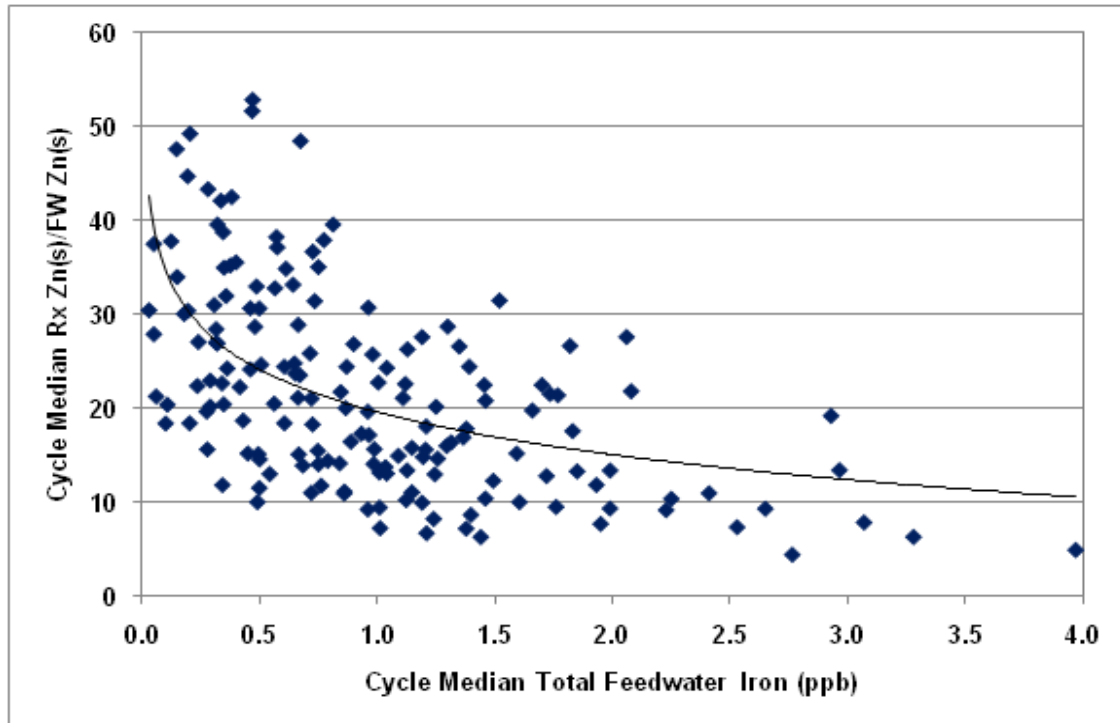


Figure 3-5
Reactor water/feedwater zinc concentration factor vs. feedwater iron

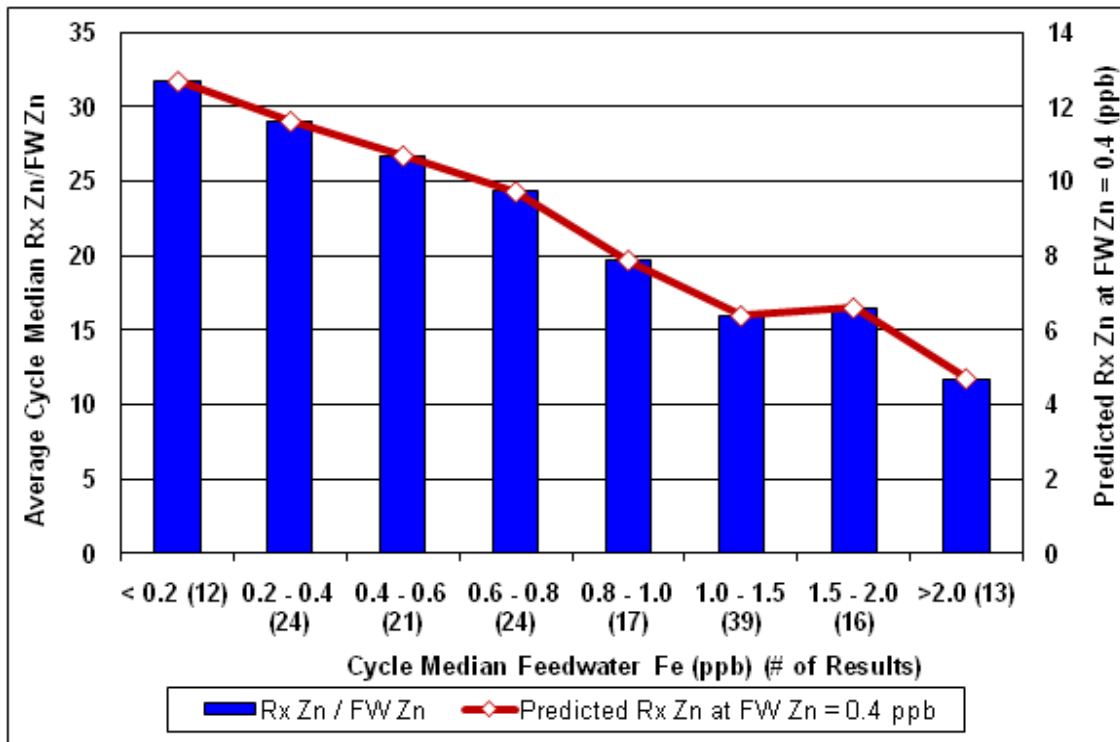


Figure 3-6
Average reactor water/feedwater zinc concentration factor vs. feedwater iron

Hotwell Iron

Average 2008 total hotwell iron concentrations from forty-five plants reporting data are shown in Figure 3-7. Hotwell iron varies widely among these plants, from about 3.5 to 33 ppb. The magnitude of the hotwell iron concentration is an indicator of the type of action that must be taken by specific plants, in particular those with Deep Bed Only condensate polishing systems, to provide sufficient removal of iron from condensate. At plants with condensate filters, higher hotwell iron concentrations result in shorter run lengths to dP endpoint, thus increasing both liquid and solid radwaste volumes. The effect of shorter filter runs on solid radwaste generation is more significant at plants with precoated filters. Hotwell iron concentrations also must be considered when selecting filter septa at plants with CF/Ds; yarn wound septa may provide adequate iron removal at plants with low hotwell iron concentrations.

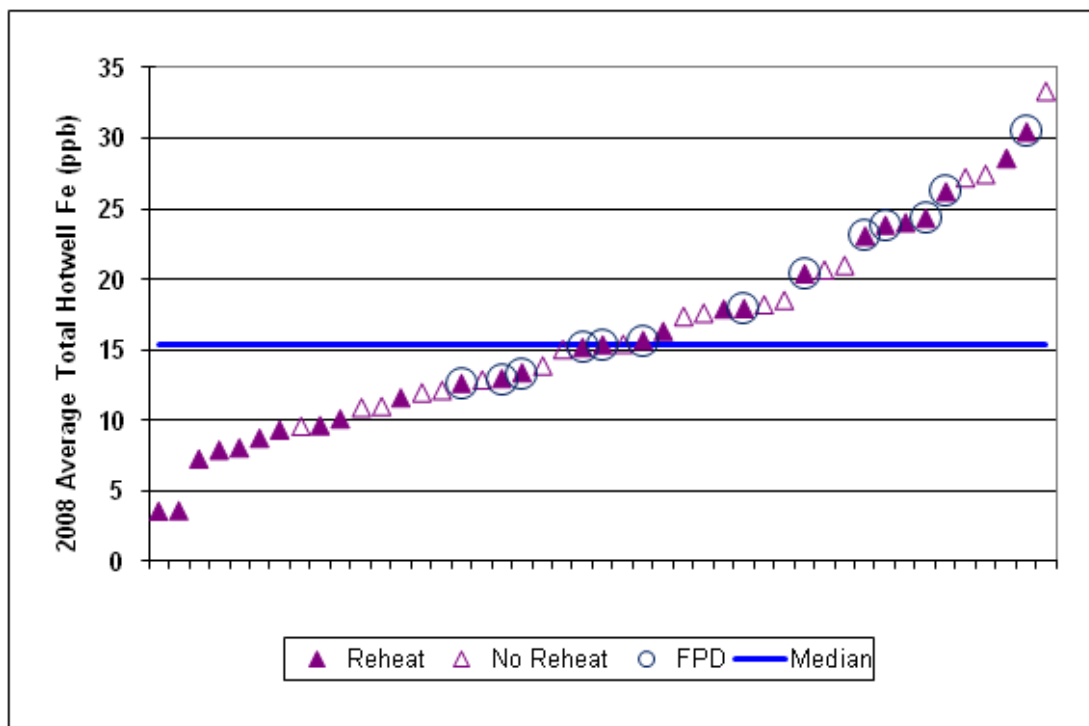


Figure 3-7
2008 average hotwell iron concentration

Fifty-two percent (52%) of plants with moisture separator reheaters had average hotwell iron less than the median value of 15.4 ppb, compared with 44% of plants without moisture separator reheaters. The data indicate that plants with forward pumped heater drains (all with reheat capability) had higher average hotwell iron in 2008 than those with cascaded drains.

When plants designed with reheat have experienced a loss in the availability of the reheaters, hotwell iron has increased dramatically. At one BWR with reheat capability, increased hotwell iron was attributed to corrosion of condenser internals. A summary of annual average hotwell iron concentrations for plants with and without moisture separator reheaters is shown in Figure 3-8. The annual averages for plants designed with reheat capability are about 15 ppb,

compared with about 20 ppb for those plants which have no reheat capability. However, the difference in annual averages between the two plant designs has decreased since 2000, when the average for plants without reheaters was 37.5% higher than that for plants with reheaters. In 2008, the difference between the average concentrations for the two plant designs has decreased to 8.8%. The performance of EPU modifications at plants with high hotwell iron and without reheat capability is most likely responsible for this change.

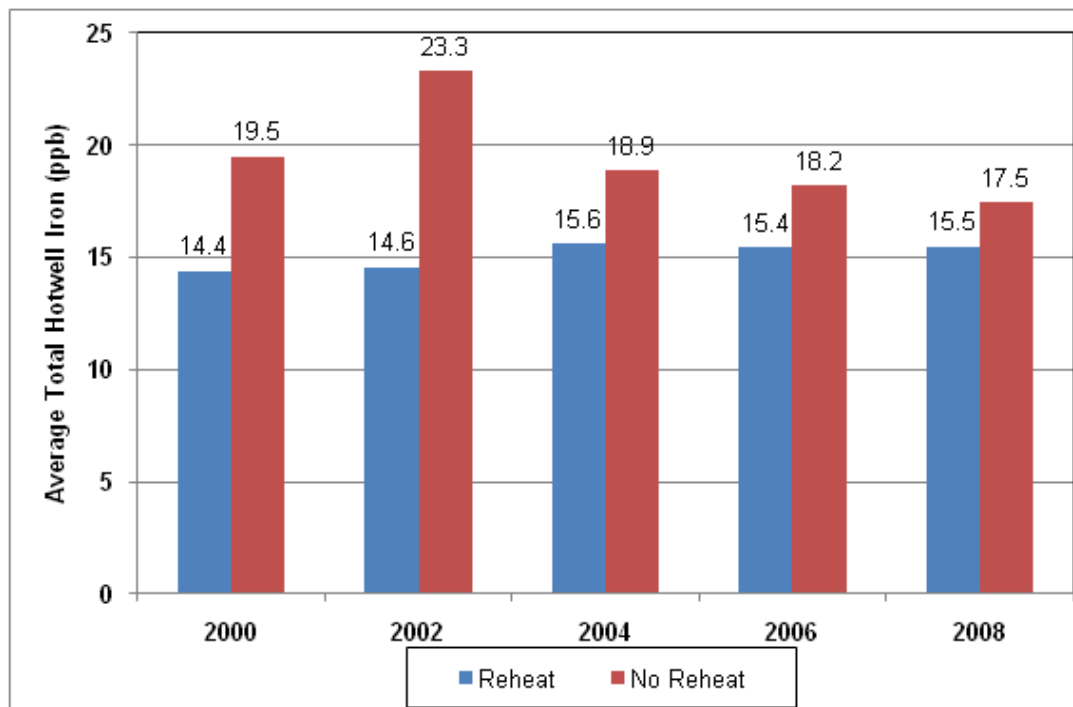


Figure 3-8
2000 – 2008 annual average total hotwell iron concentration

Some modifications that may impact iron input (for both reheat and non-reheat plants) include:

- Replacement of carbon steel extraction steam piping subject to FAC with chrome-moly steels or stainless steel clad carbon steel.
- Power uprate modifications, which may include replacement of turbines with designs having more or less corrosion.
- Replacement of carbon steel internals with stainless steel internals in moisture separators (which would affect plants with cascaded drains).
- Replacement of feedwater heaters that had been damaged by FAC with more corrosion-resistant designs.
- Repairs and improvements to condenser baffling that reduce corrosion product generation from steam impingement.

Effect of Power Uprate on Hotwell Iron Concentrations

The effect of extended power uprate on hotwell iron concentrations was discussed in the 2005 revision of the BWR Chemistry Monitoring Report [3] and updated in the 2007 revision [4]. Additional analysis in 2008 using statistical software determined the following [5]:

- The response of hotwell iron after EPU is variable and dependent upon system modifications.
- The amount of change may be related to the power increase (i.e., more increase with higher % change in power).
- Plants without MSRs exhibited greater changes in hotwell iron concentrations than those with MSRs.
- At some plants, the increase was temporary and concentrations returned to pre-EPU levels.

Leibstadt is an example of a plant with forward pumped heater drains and reheat that experienced increased hotwell iron concentrations after thermal power was increased by 462 MW (14.7%) in four steps between 1998 and 2002. The increase in hotwell iron concentration from less than 16 to about 20 ppb following the last step in 2002 can be seen in Figure 3-9. Since 2002, median hotwell iron has decreased to 18.3 ppb, about the same as after the second power uprate step. The trend will continue to be monitored to determine whether hotwell iron concentrations eventually return to the pre-EPU range.

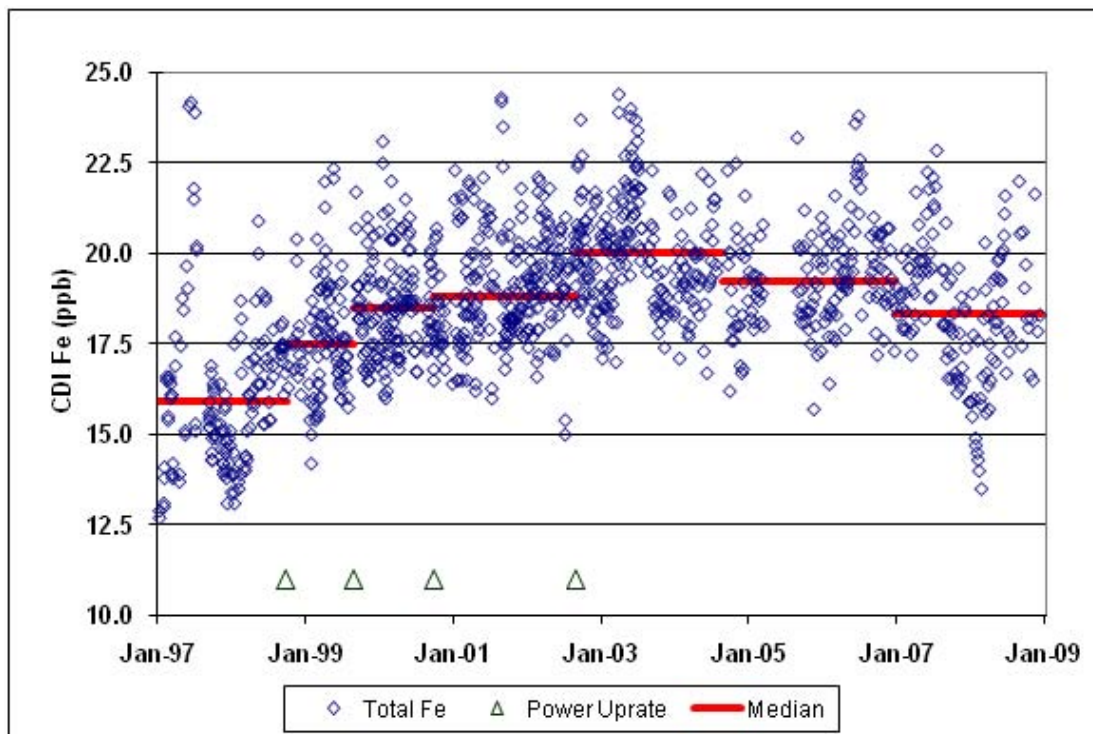


Figure 3-9
Leibstadt hotwell (CDI) iron concentration

Feedwater Copper Control

BWR Industry Copper Control Performance

Monitored BWRs with a significant copper source in the main condenser include Kuosheng 1 and 2, Columbia, FitzPatrick, Laguna Verde 1 and 2, Limerick 1 and 2, Nine Mile Point 1 and 2, Santa Maria de Garoña, River Bend, and Vermont Yankee. The ability to control feedwater copper at the lowest concentrations is clearly a function of the condensate polishing system design at these plants.

Cofrentes replaced its admiralty brass condenser tubes (Cu/Ni tubes at periphery) with titanium in September 2000. Average annual total feedwater copper was 0.16 ppb before condenser retubing and has averaged 0.03 ppb since retubing. Cofrentes, like Vermont Yankee and Columbia, uses Filter Demineralizers for condensate polishing. Columbia plans to retube its condenser with titanium in 2011 to eliminate chronic condenser leaks and prepare for license renewal. Laguna Verde 1 replaced its original Cu-Ni condenser tubes with titanium in September 2008 and Laguna Verde 2 did the same in April 2009. Vermont Yankee is also considering options to retube its condenser pending approval of license renewal.

The Limerick stations were converted to the Filter + Deep Bed configuration from the original Filter Demineralizers to improve copper control. Feedwater copper at River Bend was reduced from approximately 0.2 ppb to <0.05 ppb following the startup of prefilters. Nine Mile Point 1 installed condensate prefilters in September 2006. Since installation, average feedwater insoluble and soluble copper have decreased to less than the detectable concentration of 0.1 ppb. Since installation of condensate prefilters at Nine Mile Point 2, feedwater insoluble and soluble copper concentrations have decreased to the LLD values of 0.02 or 0.03 ppb. Industry experience has demonstrated that feedwater copper concentrations <0.05 ppb are achievable with the Filter + Deep Bed configuration.

Columbia and Vermont Yankee have reduced feedwater copper concentrations by CF/D system improvements, including installation of DualGuard™ septa. These septa have inner pleated media septa (for improved removal of insoluble copper) surrounded by a cylindrical outer precoat layer (for improved removal of soluble copper). At Vermont Yankee, integrated flow distributors were installed for better flow and precoat distribution, and an improved septa attachment method has eliminated resin leakage, allowing high cation:anion ratio precoat materials to be used for copper control.

The 2008 average feedwater total copper concentrations (numerical average of results at power >10%) for the monitored plants with a copper source in main condenser are plotted in Figure 3-10. The EPRI Action Level 1 value of >0.2 ppb is shown on the plot, as is the recommended goal of 0.05 ppb for water chemistry optimization. Feedwater copper increased at Vermont Yankee following extended power uprate (EPU) in March through May 2006; the median value for feedwater copper in 2009 after modifications were completed in all CF/Ds is less than 0.2 ppb. The average total copper at Nine Mile Point 2 is skewed high due to operation with only deep beds in early 2008; since prefilter installation in May 2008, soluble and insoluble copper have been reported at LLD values of 0.02 or 0.03 ppb.

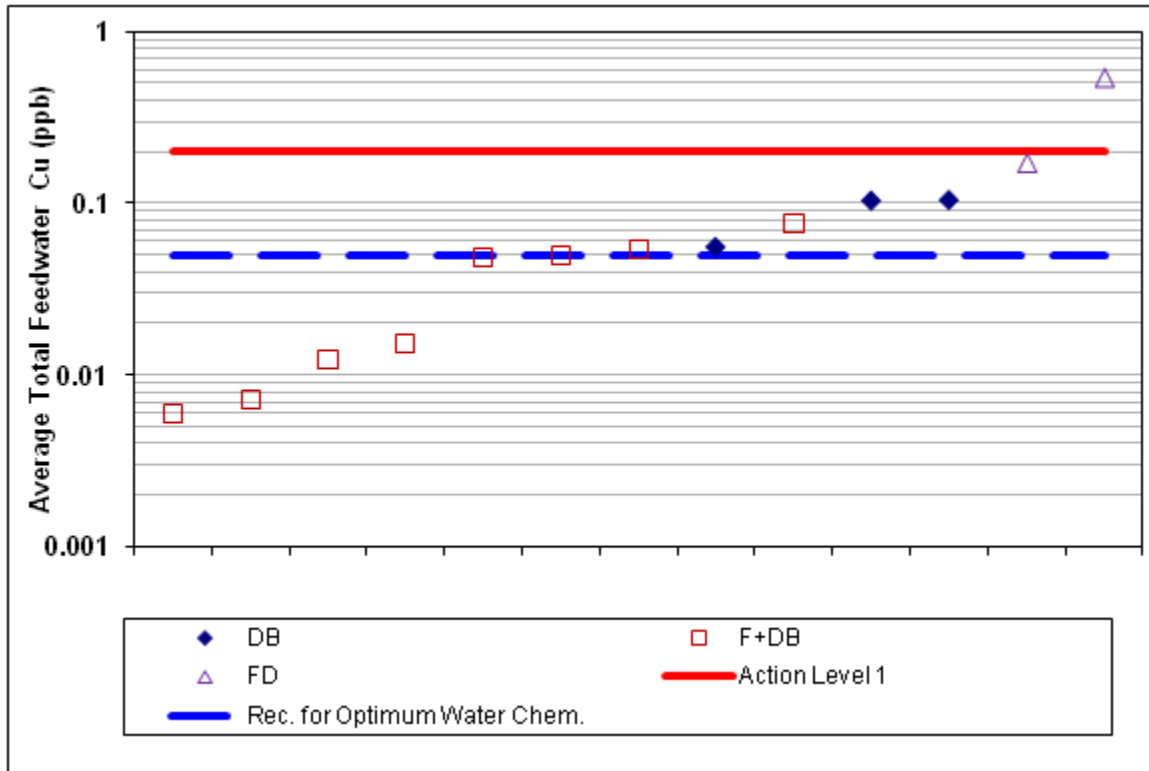


Figure 3-10
2008 average feedwater copper for BWRs with copper source in main condenser

The 2008 average feedwater total copper concentration for forty-five BWRs submitting data, differentiated by condensate polisher type and main condenser tube material, is plotted in Figure 3-11. Ten of the forty-five plants had average copper concentrations greater than the EPRI goal for water chemistry optimization of <0.05 ppb. Seven of these ten plants have a copper source in the main condenser tube materials. The value at Mühleberg is the lower limit of detection. Only one BWR exceeded the AL-1 value for feedwater copper in 2008, and CF/D system improvements have reduced feedwater copper to less than 0.2 ppb at this plant for 2009 to date.

As indicated in Figure 3-10 and Figure 3-11, Filter + Deep Bed plants can readily control feedwater copper below the optimum goal of 0.05 ppb. By implementing best practices, Deep Bed Only plants are capable of maintaining feedwater copper below the Action Level 1 value. The lower achievable feedwater copper by Filter + Deep Bed plants compared to plants with Deep Bed Only condensate polishing is attributed to the efficient removal of insoluble copper by the filters and soluble copper by large resin volume with fixed bed ion exchange (the ion exchange zone is normally not disturbed during the life of the resins). Filter Demineralizer plants with a copper source in main condenser tube materials have routinely operated with feedwater copper above Action Level 1 although, as discussed, significant progress in reducing feedwater copper at these plants has recently been made.

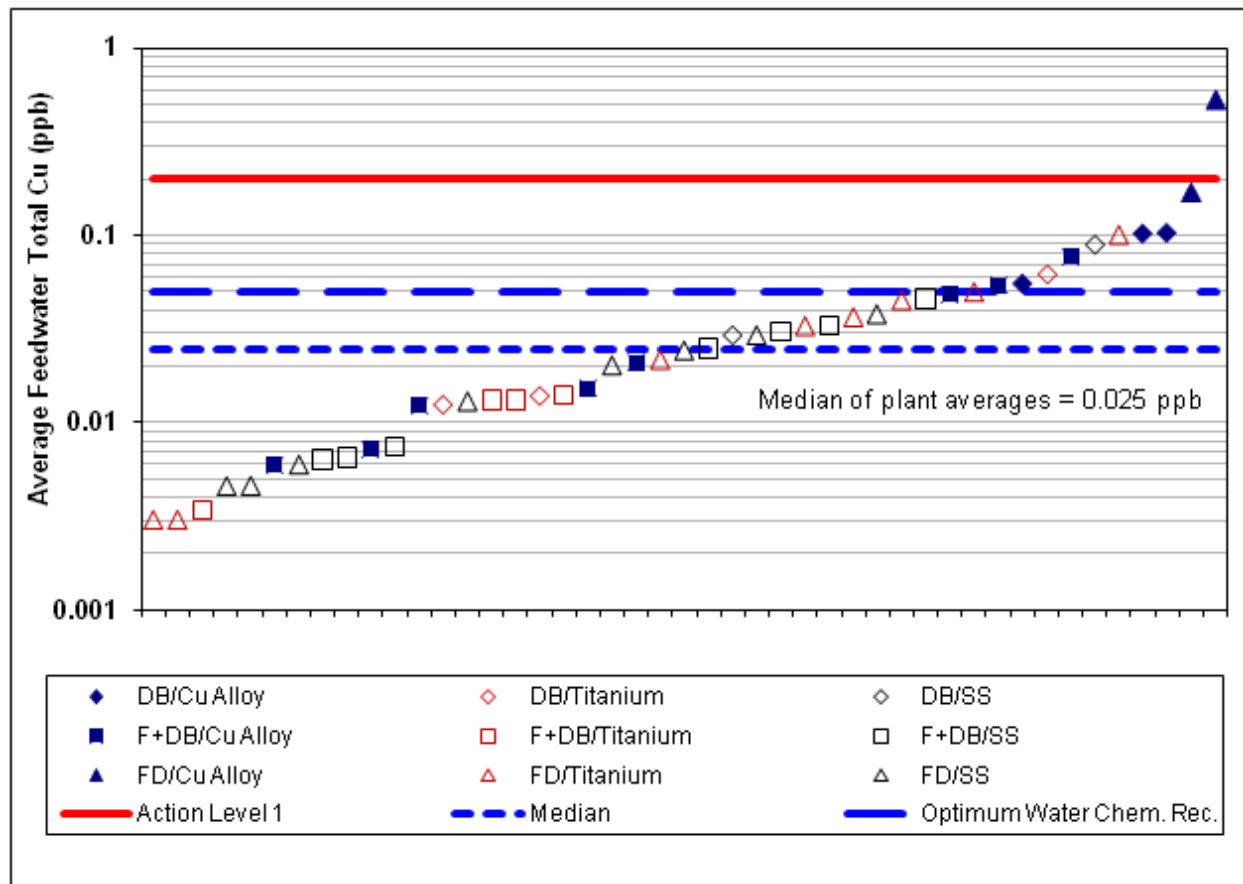


Figure 3-11
2008 average feedwater copper for BWRs differentiated by condensate polisher type and main condenser tube material

For the same group of BWRs with copper alloy condenser tubes, the 2000 - 2008 average feedwater copper concentrations for the condensate polishing system design types are shown in Figure 3-12. [Note: the number of plants increased from ten to thirteen in 2006, with two plants added in the Deep Bed Only category and one in the Filter + Deep Bed category.] The results show the strong correlation of feedwater copper concentrations with condensate polishing system design. Individual plant performance in any given year may result in significant changes in the category average, as the number of plants in each category is low.

Individual feedwater copper values for the years 2004 and 2008 are shown in Figure 3-13. Nine additional data points were available in 2008 with the addition of seven plants (Browns Ferry 1, Chinshan 1 and 2, Kuosheng 1 and 2, Santa Maria de Garona, and Ringhals 1) to the database and additional results from two BWRs. The percentage of BWRs meeting the EPRI water chemistry optimization goal of <0.05 ppb increased from 71% (24 BWRs) in 2004 to 78% (35 BWRs) in 2008.

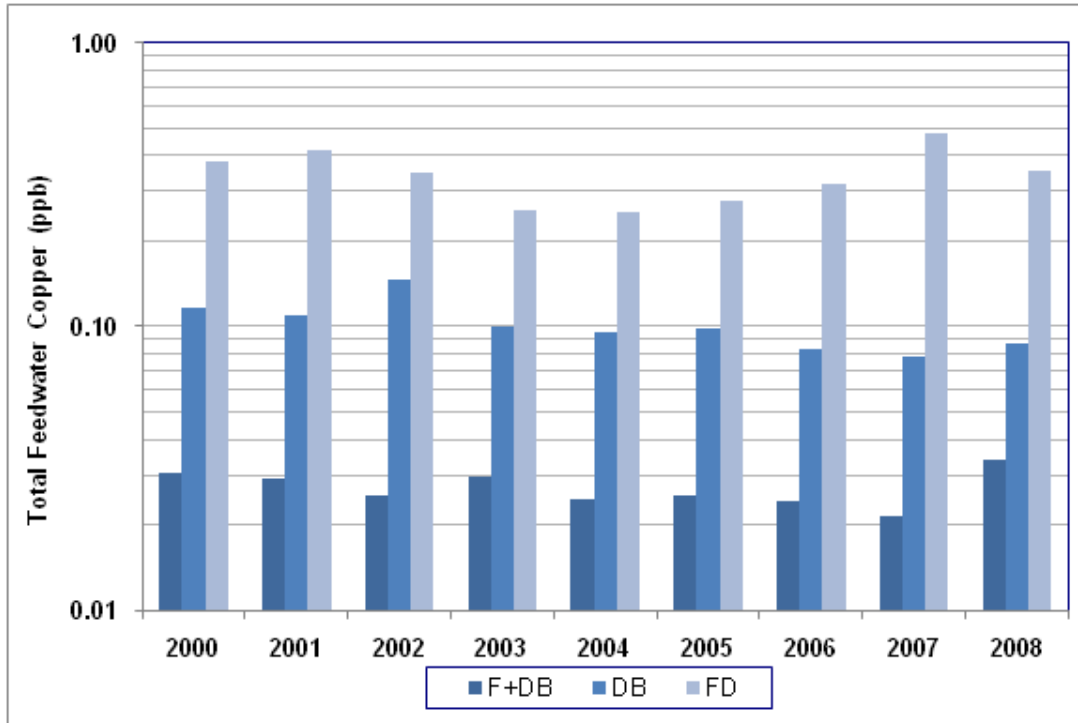


Figure 3-12
2000 – 2008 average feedwater copper differentiated by condensate polisher type (for plants with copper alloy condenser tubes)

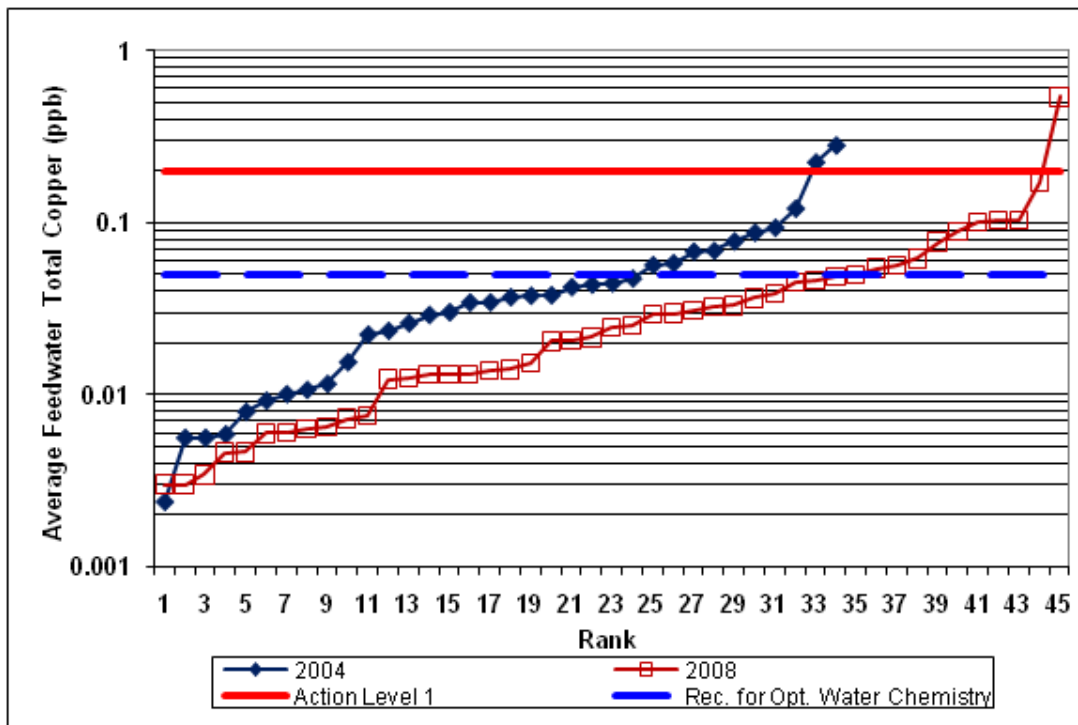


Figure 3-13
2004 and 2008 average feedwater copper

Hotwell Copper

The 2008 average hotwell copper concentrations for monitored BWRs with copper alloy condenser tubes are summarized in Table 3-5. The averages include all reported values at power >10% and are not time-weighted. The average total is calculated from individual totals and is not the sum of the insoluble and soluble averages. Average hotwell total copper ranges from about 1.3 to 5.3 ppb for these plants. The fraction reported as soluble (non-filterable through a 0.45-micron membrane filter) ranges from 47% to 89% of the sum of the average insoluble and soluble copper. The Laguna Verde units have the highest hotwell copper and FitzPatrick has the lowest among the monitored BWRs with copper alloy condenser tubes.

Comparison with the feedwater values in Figure 3-10 indicates that plants with Deep Bed Only or Filter +Deep Bed condensate polishing can achieve optimum feedwater copper even with high inlet copper.

Table 3-5
2008 average hotwell copper (BWRs with copper source in main condenser)

Plant	CP Type	Hotwell Copper (ppb)		
		Insoluble	Soluble	Total
Columbia	F/D	0.968	1.28	2.23
FitzPatrick (median)	DB	0.438	0.888	1.32
Kuosheng 1	DB	0.950	not reported	n/a
Kuosheng 2	DB	0.975	not reported	n/a
Laguna Verde 1	F+DB	2.23	2.45	4.68
Laguna Verde 2	F+DB	2.83	2.46	5.29
Limerick 1	F+DB	0.318	1.56	1.78
Limerick 2	F+DB	0.487	1.81	2.14
Nine Mile Point 1	F+DB	0.603	2.12	2.72
Nine Mile Point 2	F+DB	0.545	2.36	2.87
River Bend	F+DB	0.403	3.31	3.44
Santa Maria de Garoña	F+DB	0.712	1.55	2.26
Vermont Yankee (1)	F/D	0.659	2.21	2.87

Effect of Condensate Temperature on Hotwell Copper Concentration

The effect of condensate temperature on CPD soluble copper at Vermont Yankee is shown in Figure 3-14. The station performed an extended power uprate from 1523 to 1912 MWth in March – May 2006. The combination of higher condensate temperature after EPU, unusually warm river water temperature, and a cooling tower failure contributed to high CPD soluble

copper in the summer of 2007. The higher inlet copper to the CF/Ds resulted in high feedwater copper concentrations, near 1 ppb at times. Condensate system improvements have resulted in higher soluble copper removal efficiencies for the CF/Ds at Vermont Yankee, decreasing the effect of condensate temperature on feedwater copper concentrations.

Increased hotwell copper concentrations due to temperature effects are of greater concern for BWRs with CF/Ds due to the limited capacity for soluble species removal compared to that of plants with deep bed demineralizers.

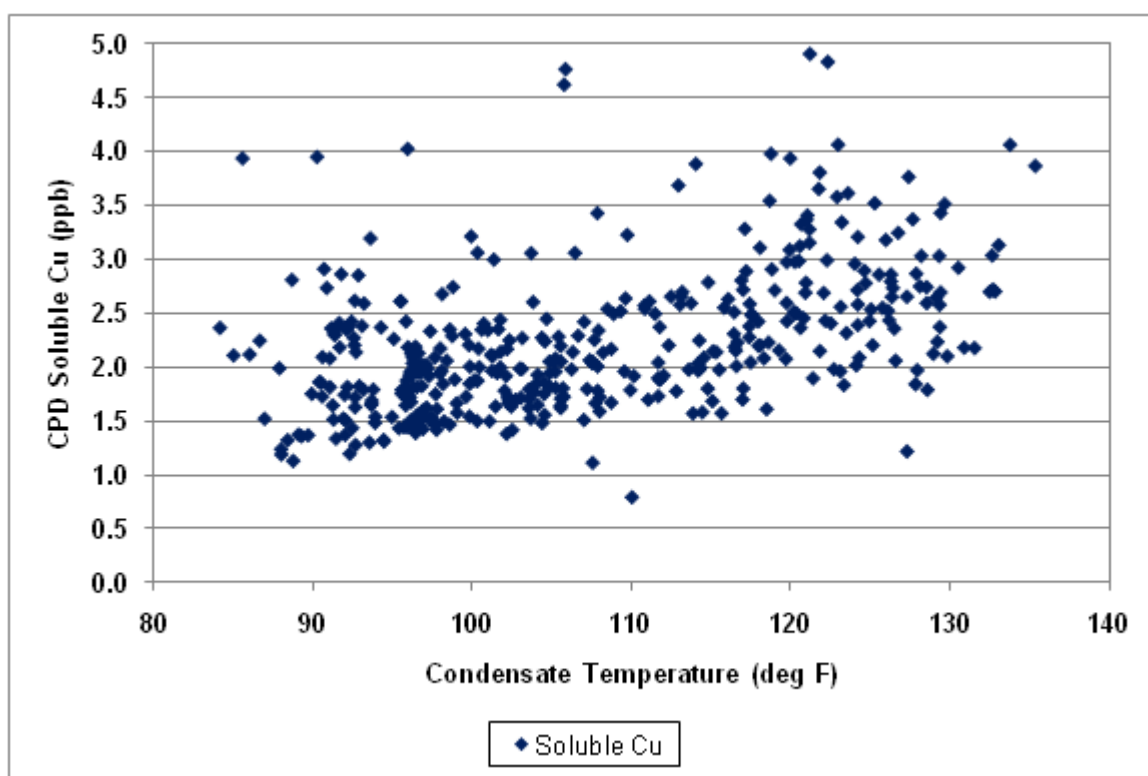


Figure 3-14
Vermont yankee CPD soluble copper (July 2006 – November 2008)

Low Iron Experience

High-efficiency iron removal filter septa that employ pleated filter media are now applied extensively in U.S. BWR condensate polishing applications (See Chapter 9). These types of septa are used without precoat materials in Filter + Deep Bed or with precoats in CF/D applications. Iron concentrations in the filter effluent below 0.1 ppb are achievable with these septa.

The minimum level of feedwater iron is dependent on several plant configuration factors, including:

- Heater drains path (cascaded or forward-pumped)
- Iron input from forward-pumped high pressure drains (for forward-pumped drains plants)

- Percentage of condensate filtered
- Septa particle retention rating
- The number of CF/D vessels with pleated septa (for CF/D plants)
- Type and dosage of precoat materials (for CF/D plants)

The EPRI BWR Water Chemistry Guidelines – 2008 Revision [1] suggests an optimum range for feedwater iron control between 0.1 ppb and 1.0 ppb for plants injecting hydrogen. Regarding low feedwater iron, this document states, “Although there have been no observed detrimental effects, there is relatively little long term data for HWC plants operating continuously below 0.1 ppb. For high cobalt source term plants, maintaining ≥ 0.1 ppb iron in the feedwater may assist in limiting reactor coolant soluble Co-60 levels. Consultation with the fuel vendor is considered a good practice when operating with <0.1 ppb (cycle average) feedwater iron.”

In the years since feedwater iron guidelines were developed, BWR operating experience with <0.1 ppb feedwater iron has increased and plant chemistry regimes have changed. Over this period, operation under HWC-M and NMCA+HWC has increased, creating reducing chemistry conditions in parts of the primary system, converting crud deposited on a portion of the fuel from the Fe_2O_3 form to the reduced Fe_3O_4 oxide form. During the transition from oxidizing to reducing conditions, activated corrosion products are released from the fuel deposits. The widespread use of DZO has been effective in limiting the incorporation of Co-60 in the primary piping corrosion films, thus maintaining or reducing shutdown radiation dose rates, and appears to have stabilized the fuel crud deposits. With fully established reducing conditions under NMCA+HWC and stabilization of the iron oxide spinel deposited on the fuel by injecting sufficient DZO, the industry data suggest that further lowering feedwater iron to <0.1 ppb can provide lower drywell radiation dose rates, particularly for low cobalt source term plants, and reduce DZO usage without increasing hot spots.

The need to maintain a minimum feedwater $\text{Fe}/(\text{Zn}+\text{Other Transition Metals})$ ratio has been investigated by EPRI with respect to fuel performance. Fuel vendors are no longer requiring a minimum ratio. More importantly, minimizing feedwater iron has the benefit of lowering the deposition of iron on the fuel, which is useful in limiting any fuel performance impact from tenacious crud deposits.

The current lower bound for feedwater iron optimization of 0.1 ppb was based on the lack of industry experience below this threshold [1]. However, operating experience with low feedwater iron has increased in recent years, as shown in Table 3-6. All of these plants operate with Filter + Deep Bed condensate polishing, and all but LaSalle 1 and Perry have cascaded drains.

Complete cycle median data for plants operating with low feedwater iron are shown in Table 3-7.

At Nine Mile Point 1, there was a 20% increase in reactor coolant Co-60 activity after the first full cycle of low feedwater iron operation. However, restructuring after implementation of OLNC (first application in December 2006) may be responsible for the increased activity. There was no change in average BRAC dose rate from EOC 17 to EOC 18.

Table 3-6
Plants with current or expected low feedwater iron operation

Plant	Median FW Fe, ppb (1)	Low Fe Operation Start Date	Number of RFOs since Low Iron Operation Began	Comments
Dresden 2	0.016	October 2007	1 (fall 2009)	Full flow condensate filtration implemented October 2007
Dresden 3	0.080 (2)	December 2008	0	Full flow condensate filtration implemented November 2008
LaSalle 1	0.080	March 2008	0	Feedwater heaters replaced January 2008
Monticello	0.073	January 2008	1	Septa particle retention ratings changed
Nine Mile Point 1	0.060	October 2006	2	Full flow condensate filtration implemented September 2006
Oyster Creek	0.130	February 2008	1	Full flow condensate filtration implemented November 2007
Perry	0.077	April 2006	2	
River Bend	0.030	March 2003	4 (includes fall 2009)	Current fuel load has only been exposed to low feedwater iron. Full flow condensate filtration implemented in late 2002.

Notes

2008 or latest 12 months' data.

Dec 2008 – August 2009.

Perry has operated with feedwater iron near or less than 0.2 ppb for the past 10 years. There was an increase in Co-60 activity after NMCA was first applied at the beginning of Cycle 9. Since then, Co-60 activity has been on a decreasing trend as feedwater iron has decreased. Increased BRAC dose rates at Perry are attributed to high cobalt source term and implementation of HWC after NMCA.

River Bend is the lead plant for long term operation with feedwater iron <0.1 ppb under reducing conditions (HWC-M) and DZO injection. Operation at <0.1 ppb feedwater iron began shortly after installation of full flow condensate filtration in late 2002. During three subsequent refueling outages (18-month fuel cycle), fuel that had been exposed to high feedwater iron operation was replaced. Cycle median Co-60 activity at River Bend is shown in Figure 3-15. Insoluble Co-60 has decreased an order of magnitude from 3.5E-4 µCi/ml during Cycle 11 to 3.0E-5 µCi/ml during Cycle 15. Soluble activity increased from 5.7E-4 to 1.2E-4 µCi/ml during the first cycle of low feedwater iron operation, but has shown a decreasing trend since Cycle 12.

Table 3-7
Cycle median data for BWRs with low feedwater iron

Plant	Cycle	Dates	BRAC	FW Fe	FW Zn	Reactor Water Co-60			
			mR/hr	ppb	ppb	Insol.	Sol.	Total	Sol. Fraction
						μCi/ml	μCi/ml	μCi/ml	%
Nine Mile Point 1	17	4/05 – 3/07	137	0.840	0.600	2.02E-5	1.35E-4	1.64E-4	87.0
Nine Mile Point 1	18	4/07 – 3/09	134	0.060	0.450	2.99E-5	1.70E-5	1.95E-4	85.0
Perry	8	5/99 – 2/01	245	0.382	0.144	3.88E-5	6.03E-5	9.91E-5	60.9
Perry	9	3/01 – 5/03	265	0.349	0.204	1.56E-4	1.65E-4	3.38E-4	51.4
Perry	10	5/03 – 2/05	505	0.275	0.494	8.22E-5	1.43E-4	2.38E-4	63.5
Perry	11	5/05 – 4/07	965	0.146	0.201	7.71E-5	1.37E-4	2.25E-4	64.0
Perry	12	5/07 – 2/09	733 (1)	0.073	0.367	3.85E-5	6.10E-5	1.06E-5	61.3
River Bend	11	10/01 – 4/03	573	3.168	0.524	3.46E-4	5.72E-5	9.67E-4	12.8
River Bend	12	4/03 – 11/04	316	0.050	0.170	1.49E-4	1.24E-4	3.12E-4	45.3
River Bend	13	11/04 – 4/06	364 (2)	0.030	0.160	2.33E-5	1.15E-4	1.84E-4	83.2
River Bend	14	5/09 – 3/08	648 (3)	0.050	0.210	7.04E-5	1.15E-4	4.31E-4	62.1
River Bend	15 (4)	3/08 – 9/09	318	0.030	0.260	3.03E-5	7.98E-5	1.62E-4	72.5

Table 3-7 Notes

1. Pre-decon
2. Value is corrected for empty pipe. Measured value is 430 mR/hr.
3. Pre-decon; post-decon value = 71 mR/hr.
4. Data through 6/30/09; RFO started 9/21/09.

The BRAC dose rate trend at River Bend is shown in Figure 3-16. The average BRAC dose rate decreased from 573 mR/hr at EOC 11 to less than 400 mR/hr at EOC 12 and EOC 13. During Cycle 14, average BRAC increased to 648 mR/hr. A recirculation system chemical decontamination was performed, reducing the BRAC dose rate to 71 mR/hr. Average BRAC dose rates increased to 318 mR/hr at the end of Cycle 15. There is no apparent correlation between the increased BRAC dose rate and reactor coolant Co-60 activity at River Bend. (Additional information on BRAC dose rates can be found in Chapter 5 of this report.) Permanent shielding has been installed in the drywell to minimize radiation exposure to personnel. The station plans to evaluate the need for iron injection.

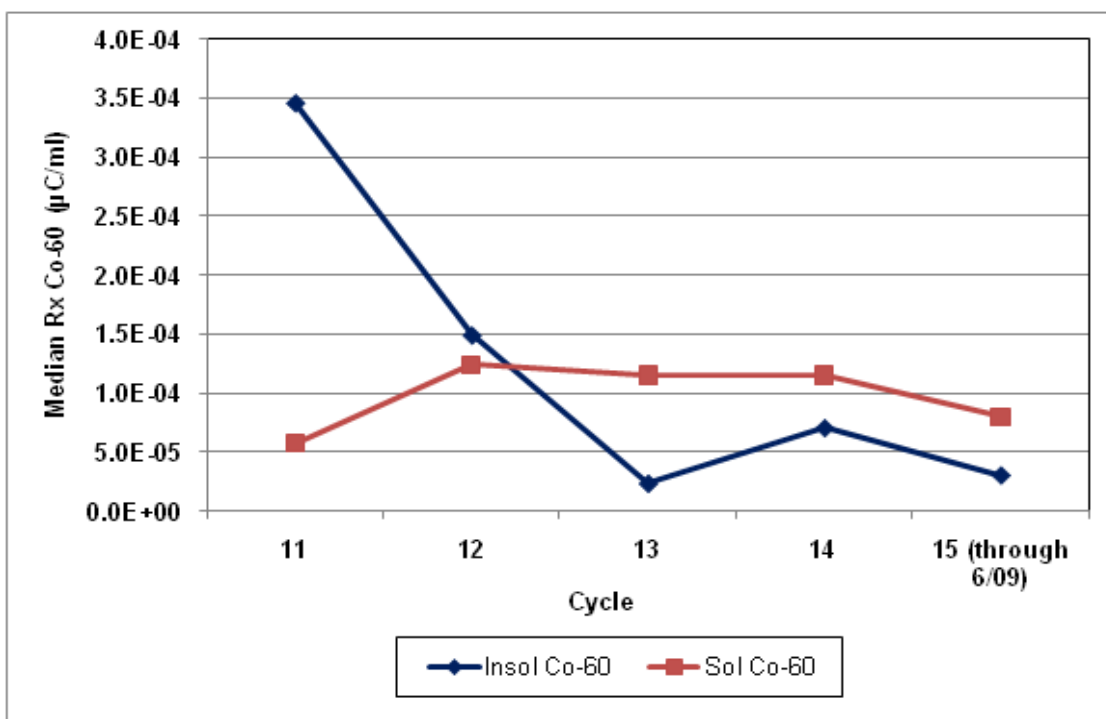


Figure 3-15
River bend cycle median Co-60

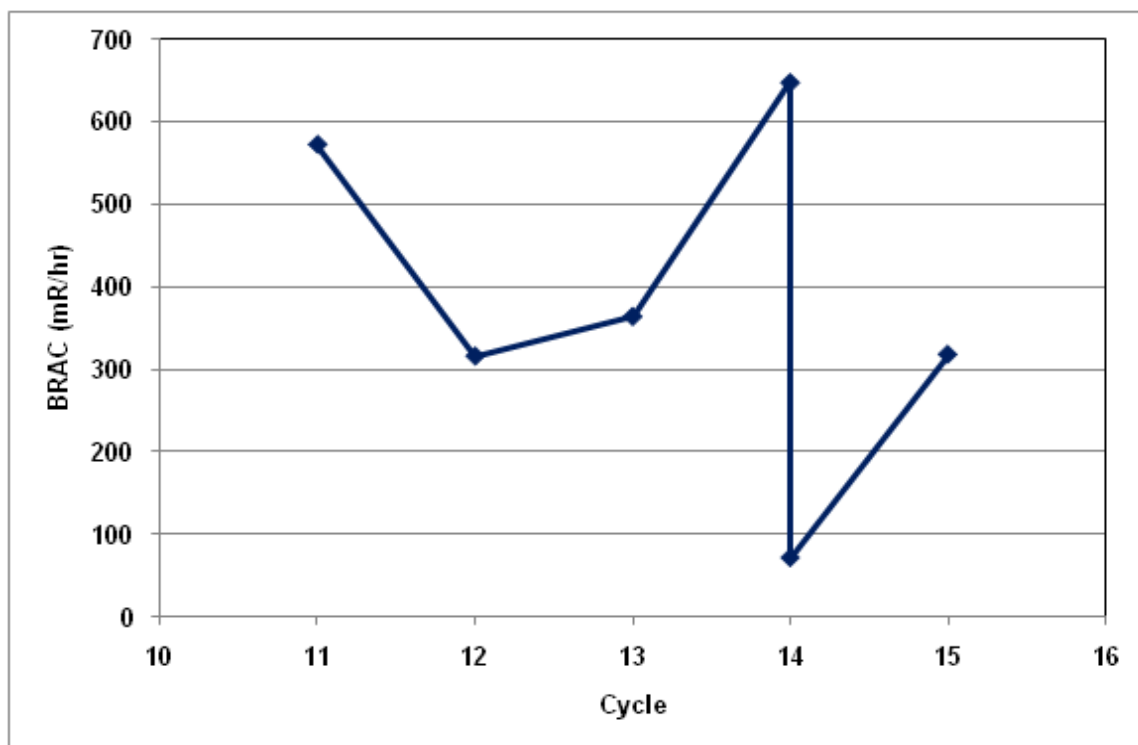


Figure 3-16
River bend BRAC dose rate trend

Reactor water Co-60(s)/Zn(s) and reactor water Zn/feedwater Zn for plants with low feedwater iron operation are shown in Table 3-8. At Nine Mile Point 1, the reactor water Co-60(s)/Zn(s) ratio was maintained $<2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ with lower feedwater zinc despite increased soluble Co-60 in the cycle following prefilter installation due to the increased zinc concentration factor. For the past three cycles, Perry has maintained the reactor water Co-60(s)/Zn(s) ratio well below the EPRI goal of $<2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ with feedwater zinc concentrations less than 0.4 ppb.

Ratio trends at River Bend are shown in Figure 3-17. The zinc concentration factor increased from 16 during high iron operation to 30 – 45 with lower feedwater iron. However, the zinc injection rate during Cycles 12 and 13 was not high enough to maintain the reactor water Co-60(s)/Zn(s) ratio below the EPRI goal. During Cycles 14 and 15, the ratio was maintained $<2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ with feedwater zinc concentrations well below 0.4 ppb. There appears to be no correlation between the reactor water Co-60(s)/Zn(s) ratio and BRAC dose rates at River Bend; the data suggest an inverse relationship. Chemistry influences on BRAC dose rates are discussed in detail in Chapter 5 of this report.

Table 3-8
Cycle median ratio data for BWRs with low feedwater iron

Plant	Cycle	Dates	Rx Zn(s)	Rx Zn(t)	FW Zn	Rx Co-60(s)	Rx Co-60(s)/Zn(s)	Rx Zn/ FW Zn
			ppb	ppb	ppb	$\mu\text{Ci/ml}$	$\mu\text{Ci/ml/ppb}$	ppb/ppb
Nine Mile Point 1	17	4/05 – 3/07	8.48	8.64	0.600	1.35E-4	1.59E-5	14.4
Nine Mile Point 1	18	4/07 – 3/09	9.36	9.68	0.450	1.70E-5	1.82E-5	21.5
Perry	8	5/99 – 2/01	6.00	6.00	0.144	6.03E-5	1.01E-5	41.7
Perry	9	3/01 – 5/03	6.95	6.95	0.204	1.65E-4	2.37E-5	34.1
Perry	10	5/03 – 2/05	9.30	9.30	0.494	1.43E-4	1.54E-5	18.8
Perry	11	5/05 – 4/07	9.20	9.20	0.201	1.37E-4	1.49E-5	45.7
Perry	12	5/07 – 2/09	10.3	10.3	0.367	6.10E-5	5.92E-6	28.1
River Bend	11	10/01 – 4/03	7.01	8.35	0.524	5.72E-5	8.16E-6	15.9
River Bend	12	4/03 – 11/04	5.63	5.75	0.170	1.24E-4	2.20E-5	33.8
River Bend	13	11/04 – 4/06	4.88	4.88	0.160	1.15E-4	2.36E-5	30.5
River Bend	14	5/09 – 3/08	5.86	6.20	0.210	1.15E-4	1.96E-5	29.5
River Bend	15 (through 6/09)	3/08 – 9/09	10.6	11.8	0.260	7.98E-5	7.53E-6	45.4

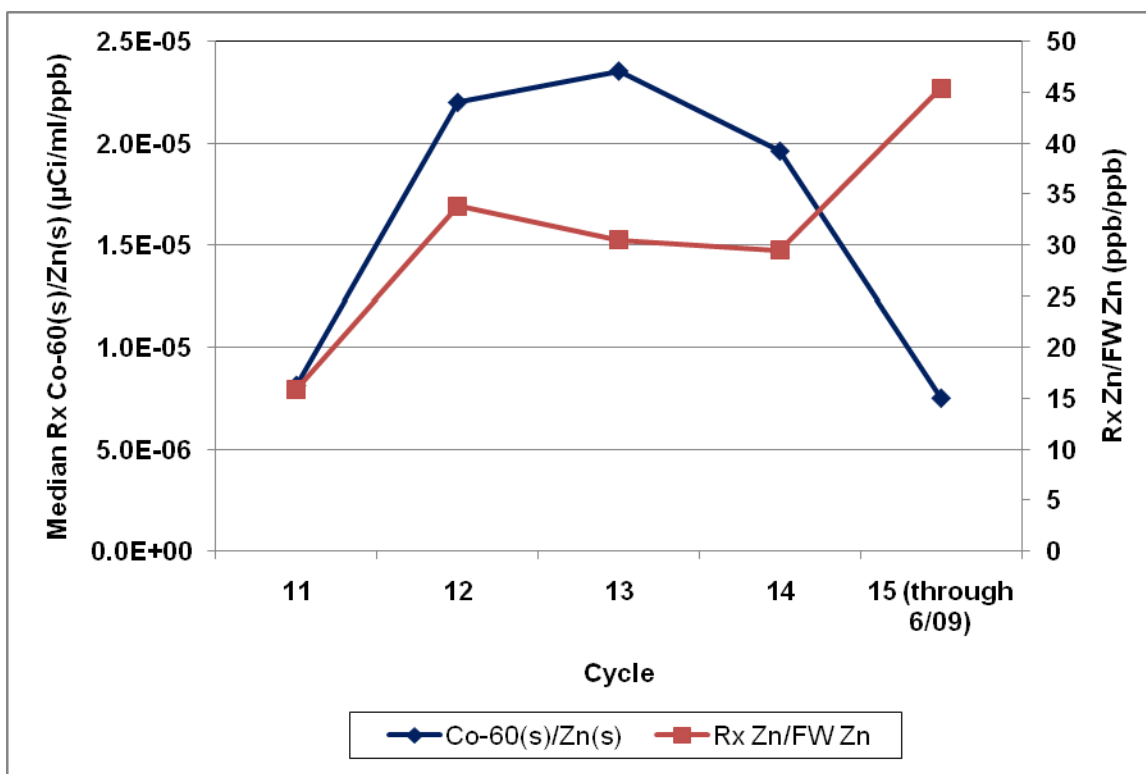


Figure 3-17
River bend cycle median Rx Co-60(s)/Zn(s) and Rx Zn/FW Zn

Recommendations for Plants Operating with Low Feedwater Iron

Due to the inventory of iron in the reactor, a plant that has transitioned from high iron to <0.1 ppb iron will not be a true “low iron” plant for at least three refueling outages after initial low iron operation. Specific recommendations for plants operating with <0.1 ppb feedwater iron are listed below:

1. For fuel reliability, inform the organization responsible for nuclear fuel performance and consult with the fuel vendor if long term operation with <0.1 ppb feedwater iron is adopted [1].
2. Continue to monitor reactor water Co-60(soluble)/Zn(soluble) through measurement of soluble and insoluble activated corrosion products weekly (minimum) and reactor water soluble zinc (weekly) [1].
3. Maintain the Co-60(soluble)/Zn(soluble) ratio below $2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ to suppress Co-60 incorporation into piping films [1].
4. Plants operating with <0.1 ppb feedwater iron should perform weekly integrated sampling for feedwater corrosion products. Pulling the feedwater samples weekly allows for the lowest detection levels for iron and other metals while meeting the minimum sampling frequency recommended by the BWR Water Chemistry Guidelines. The need for changes to the fuel warranty to allow weekly sample should be evaluated for each plant [1].

Other Considerations for Plants Operating with Low Feedwater Iron

1. Each plant operating with <0.1 ppb feedwater iron should consider having a contingency plan for implementation of iron injection if it is determined to be needed or have a significant benefit. Trends that would indicate a need for iron injection are expected to be gradual. The need for iron injection will be site specific, and the following factors should be considered:
 - Cobalt source term
 - Iron source in forward pumped drains or from condensate filter bypassing
 - Co-60 and Co-60(soluble)/Zn(soluble) trends
 - Site-specific maximum feedwater zinc
 - Reactor water metals and activated corrosion products, particularly nickel and Co-58, that could indicate the transition to a different crud and oxide form
 - Dose rate history
 - Three-cycle rolling average feedwater iron
 - Operating history (scrams, HWC system trips, etc.)
2. As the reactor water to feedwater zinc concentration factor increases with operating time at <0.1 ppb feedwater iron, plants desiring to reduce the feedwater zinc concentration should do so slowly to minimize transport of zinc from the fuel to the reactor coolant, which may be accompanied by increased Co-60 transport to the coolant. In addition to reactor water and feedwater zinc, reactor water Zn-65 should be trended as an indicator of changes in zinc transport from the fuel to the reactor coolant.
3. In addition to zinc, monitor reactor water soluble and insoluble metals, particularly nickel. If reactor water nickel increases to several ppb and remains stable in this concentration range, this could indicate a transition to NiO in the piping oxide film, which could lead to an increased rate of Co-60 deposition. Under such conditions, iron injection should be considered to change the form to Fe_2NiO_4 which should decrease the Co-60 deposition rate based on Japanese experience [6, 7, 8]. However, it should be noted that the Japanese experience is without zinc injection, and the Co-60 deposition rate with increased nickel oxide in the oxide film and several ppb zinc in the reactor water is unknown. River Bend has not observed an increase in reactor water nickel after four refueling outages since the transition to <0.1 ppb feedwater iron.
4. Trend reactor water soluble and insoluble Co-58, an activation product of nickel, which may indicate a change to a nickel-based primary crud form.
5. Trend other activated corrosion products, including Mn-54 as an indicator of iron deficiency in primary system crud, reactor water Fe-59 to assure no instability in crud deposited on the fuel during high feedwater iron operating cycles and Cr-51 as an indicator of a stable chromium oxide deposit in the primary system under hydrogen water chemistry conditions.

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4

CHEMISTRY AND FUEL RELIABILITY

BWR fuel and core components are exposed to reactor water and steam and, in common with other heat exchangers, are subject to corrosion and fouling reactions that can impair performance and lead to perforation of the heat transfer boundary. Corrosion-induced leakage of fuel cladding has caused major economic damage due to loss of generation, early discharge of nuclear fuel and the costs of failure analyses. Additionally, activation and later release of system corrosion products from fuel surfaces produce radiation fields near external piping systems that cause radiation exposure to plant personnel. This chapter reviews aspects of water chemistry control that may affect fuel reliability.

BWRVIP-190 Guidance

Chapter 5 of the BWR Water Chemistry Guidelines – 2008 Revision [1] provides detailed information on fuel integrity, fuel surveillance, and the impact of water chemistry on fuel reliability. The BWR Fuel Reliability Guidelines [2] specify a **Mandatory** requirement that a fuel crud and cladding risk assessment be performed each cycle.

The following practices have been shown to reduce fuel crud [1]:

- Reduce feedwater iron input by improved operation of or upgrades to the condensate treatment system and/or replacement of carbon steel with more corrosion resistant materials to achieve the feedwater iron goal of 0.1 to 1.0 ppb.
- Reduce the input of copper through removal by the condensate treatment system or replacement of copper alloy condenser tube materials.
- Operate the condensate treatment and RWCU systems at high capacity and efficiency to achieve reactor water goals.
- Maintain feedwater oxygen within the Action Levels (<30, >200 ppb) to minimize FAC of carbon and low alloy steels in condensate and feedwater system piping and components. (See Chapter 7 for a discussion of feedwater oxygen.)

BWRVIP-190 **Good Practice** and **Needed** values for parameters related to fuel reliability are listed below [1]. **Needed** requirements are those considered important to long term operability but that could be subject to legitimate deviations due to plant differences and special situations [1]. **Good Practices** are not specifically identified as “mandatory” or “needed” but are important to long term operation, including the areas of materials degradation, fuel performance, and radiation exposure control [1].

- Total feedwater iron (control parameter)
 - **Good Practice** – 0.1 – 1.0 ppb
 - **Needed** – Action Level 1 >5.0 ppb
 - **Needed** – The quarterly average FW Fe concentration should not exceed 3.0 ppb. (Inform organization responsible for nuclear fuel performance if quarterly average is exceeded.)
 - **Needed** – ≤ 3 ppb quarterly average if FW Zn+Cu ≤ 0.5 ppb. (Inform organization responsible for nuclear fuel performance if quarterly average is exceeded.)
 - **Needed** – ≤ 2 ppb quarterly average if FW Zn+Cu ≥ 0.5 ppb. (Inform organization responsible for nuclear fuel performance if quarterly average is exceeded.)
 - **Needed** – Consult with fuel vendor if long term operation with FW Fe(t) <0.1 ppb is adopted.
- Total feedwater copper (control parameter)
 - **Good Practice** – <0.05 ppb
 - **Needed** – Action Level 1 >0.20 ppb
 - **Needed** – Quarterly average FW Cu should not exceed 0.1 ppb. HWC-M plants must control feedwater copper so that the reactor water copper concentration does not exceed values that reduce the effectiveness of hydrogen injection. (Inform organization responsible for nuclear fuel performance if quarterly average is exceeded.)
- Total feedwater zinc (control parameter)
 - **NMCA Plants Needed** – <0.5 ppb quarterly average AND <0.4 ppb cycle average. (Inform organization responsible for nuclear fuel performance if quarterly or cycle average is exceeded.)
 - **HWC Plants Needed** – <0.6 ppb quarterly average. (Inform organization responsible for nuclear fuel performance if quarterly average is exceeded.)
 - **Needed** – Inform the organization responsible for nuclear fuel performance if higher feedwater zinc is needed for radiation field control.
- Reactor water silica (diagnostic parameter)
 - **Good Practice** – ≤ 300 ppb quarterly average with zinc injection or $\leq$ a higher value within plant experience levels based on an assessment of the effect of elevated silica on fuel performance. If the quarterly average silica concentration exceeds 300 ppb or the plant-specific higher value, consult the fuel vendor.

Additional guidance from the BWR Fuel Reliability Guidelines [2] is found in Chapter 5 of the BWR Water Chemistry Guidelines – 2008 Revision [1].

Chemistry Parameters Related to Fuel Reliability

Feedwater Iron

Feedwater iron was discussed in detail in Chapter 3. In 2008, feedwater iron concentrations were in the desired range of 0.1- 1.0 ppb for thirty-two of the forty-six BWRs. Four plants had annual averages less than 0.1 ppb, while ten plants had averages greater than the desired range. Only two BWRs had annual averages greater than 2 ppb.

Feedwater Copper

Feedwater copper was discussed in detail in Chapter 3. In 2008, ten of the forty-five plants for which data were available had average copper concentrations greater than the EPRI goal for water chemistry optimization of <0.05 ppb. Seven of these ten plants have a copper source in the main condenser tube materials. Only one BWR exceeded the AL-1 value for feedwater copper in 2008, and CF/D system improvements have reduced feedwater copper to less than 0.20 ppb at this plant for 2009 to date.

Reactor Water Silica

The latest median values for reactor water silica for forty-two plants, forty-one of which inject DZO, are shown in Figure 4-1. All values are less than the good practice value of 300 ppb, and for more than half of the plants, the values are less than 100 ppb. The four plants with the lowest reactor water silica have deep bed demineralizers in their reactor water cleanup systems. Values are not shown for four BWRs that do not inject zinc; at these stations, values ranged from 500 – 1500 ppb.

Silica is removed during plant operation by ion exchange resins in the condensate polisher and reactor water cleanup systems (RWCU). Many plants with filter demineralizer RWCU systems allow them to operate past the point of silica break as long as the reactor water concentration is within plant administrative limits. At all but the four plants with RWCU deep beds, reducing silica would be accomplished by an increase in the frequency of backwashing and precoating RWCU filter demineralizers, which would result in increased operating costs. Once the silica inventory is reduced, the ongoing operating cost impact may be minor.

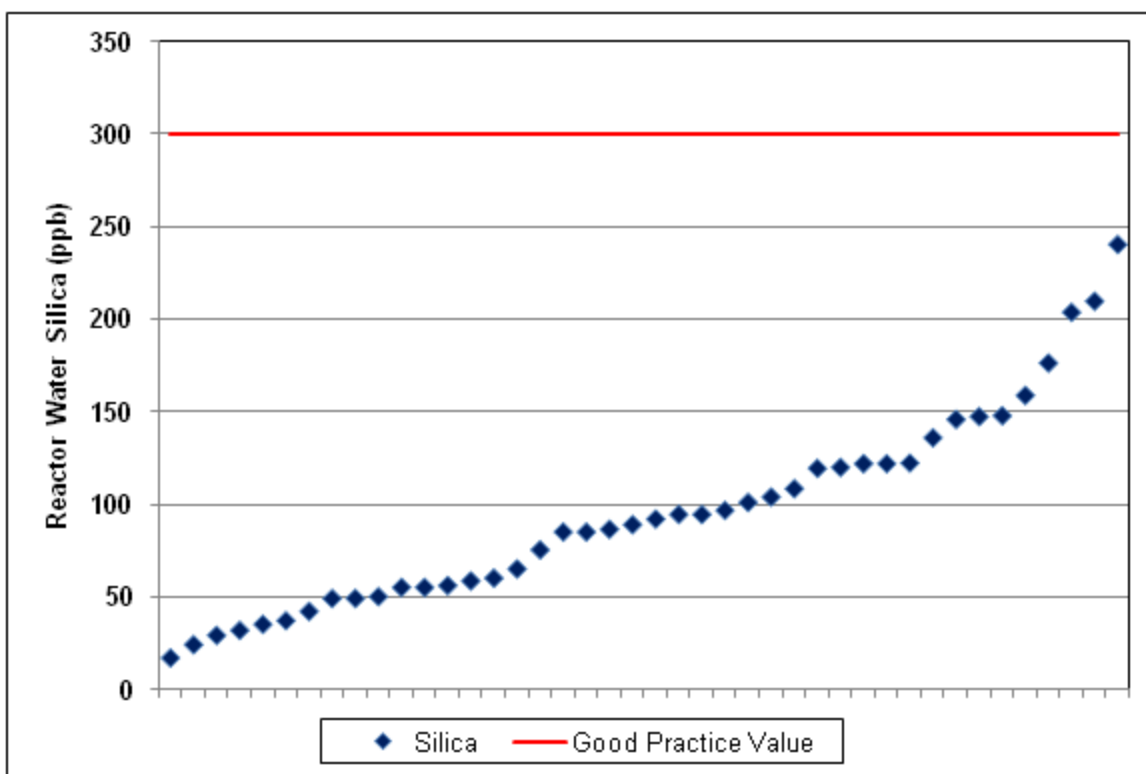


Figure 4-1
Median reactor water silica (most recent one year's data)

Feedwater Zinc

The BWRVIP-190 Chapter 7 recommendations for feedwater zinc concentration are dependent on the chemistry regime [1]:

HWC-M ≤ 0.6 ppb (quarterly average)

NMCA+HWC ≤ 0.5 ppb (quarterly average) and ≤ 0.4 ppb (cycle average)

The latest median feedwater zinc values for forty-five BWRs, differentiated by chemistry regime, are shown in Figure 4-2. Median total zinc at all HWC plants (and one NWC plant) was well below 0.6 ppb. Quarterly average values are not available, but the one year median values suggest that most plants were not likely to have exceeded 0.6 ppb in any given quarter. The five BWRs with the lowest feedwater zinc median values do not currently inject zinc for radiation field control.

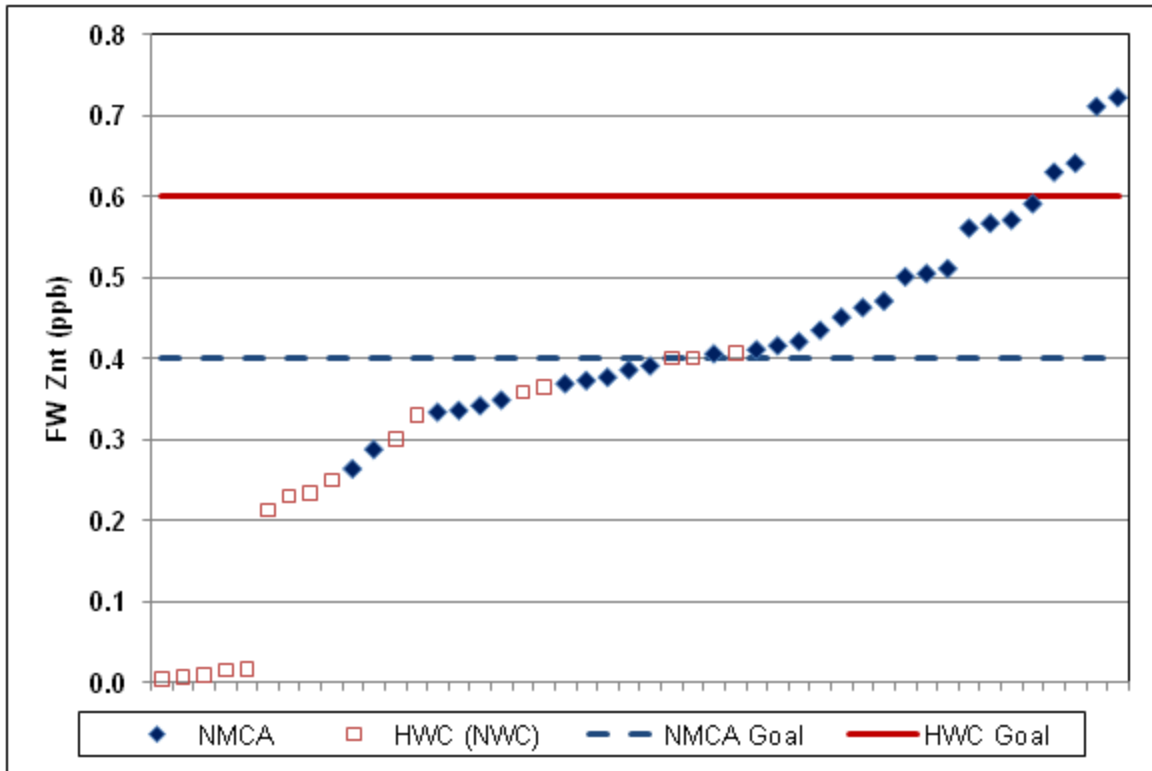


Figure 4-2
Median feedwater total zinc (most recent one year's data)

The median total zinc value at most NMCA plants was greater than 0.4 ppb, and at ten plants, was greater than 0.5 ppb, indicating that these ten plants did not meet either the cycle average or quarterly average goal for feedwater total zinc.

BWR fleet feedwater zinc trends are shown in Figure 4-3. Since 2005, there has been a decrease in the percentage of BWRs with feedwater zinc less than 0.4 ppb, and the fleet median feedwater zinc has increased from 0.36 ppb to just under 0.40 ppb.

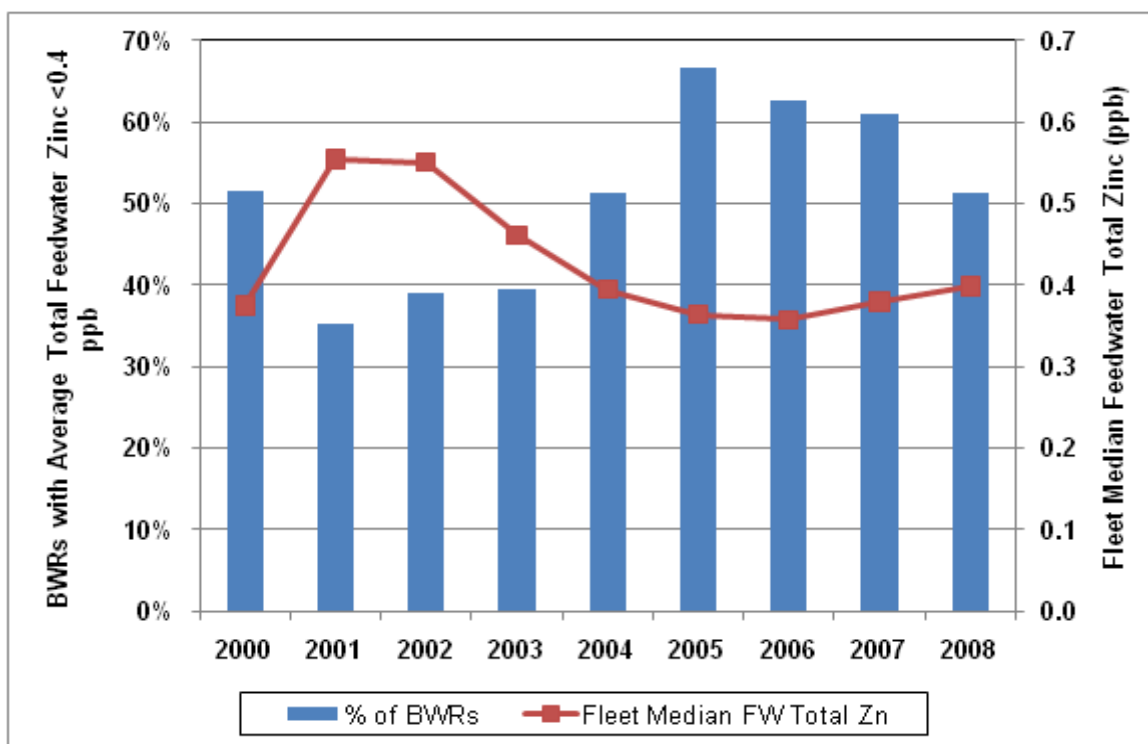


Figure 4-3
BWR fleet feedwater zinc trends (2000 – 2008)

Reactor Water Zinc

The reactor water zinc concentration has not been identified as an independent variable affecting fuel reliability or spallation. At a given feedwater flow, feedwater zinc concentration, and RWCU flow rate, a higher reactor water zinc concentration corresponds to a lower fraction of the total zinc input that deposits in the fuel and a lower reactor water Co-60(s)/Zn(s) ratio for shutdown radiation field control. The reactor water to feedwater zinc concentration factor increases as feedwater iron decreases, as shown previously in Chapter 3. Because of these relationships, dose control and fuel reliability control goals must often be balanced to meet plant specific goals. An EPRI project to evaluate zinc use at BWRs is underway with a report to be published in 2010.

Zinc is injected into the reactor coolant system to control shutdown radiation fields. Prior to widespread implementation of NMCA+HWC, the recommended reactor water control range was 5 to 10 ppb soluble zinc. Operation at the high end of the range was recommended after an outage in which a chemical decontamination of recirculation system piping had been performed. There is no current recommendation for reactor water zinc concentration in the BWR Water Chemistry Guidelines [1].

Median values for reactor water zinc are shown in Figure 4-4. The median value for this data set is 8.2 ppb and the average is 10.4 ppb for NMCA plants and 8.6 ppb for HWC plants with zinc injection. The current industry median for reactor water soluble zinc is 7.7 ppb. Seven BWRs had median concentrations <5 ppb (four of the seven do not inject DZO), and nineteen were >10 ppb, compared with eleven when this report was last published in 2007 [3].

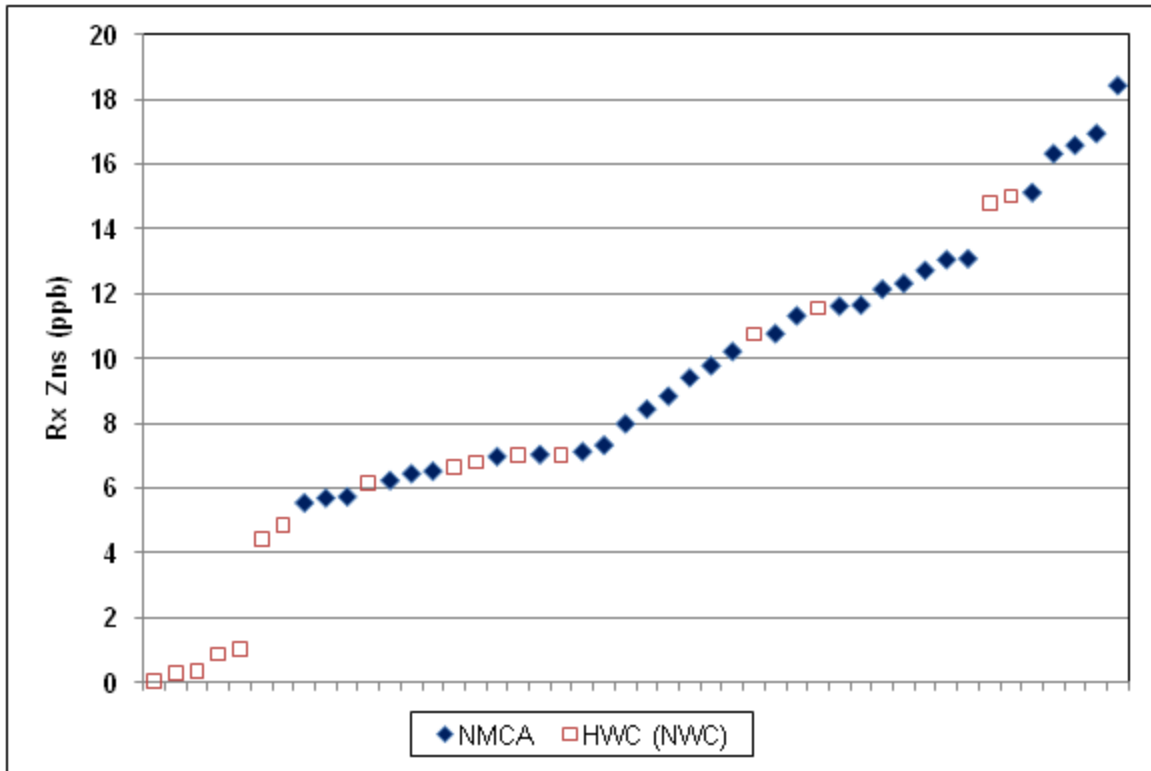


Figure 4-4
Median reactor water soluble zinc (latest one year's data)

Evaluation of Reactor Water and Feedwater Zinc Data

As noted previously, seven plants had median values for reactor water zinc below 5 ppb, and nineteen were above 10 ppb. The chemistry parameters that influence the reactor water zinc concentration for each of the plants with reactor water zinc greater than 10 ppb are shown in Table 4-1. These values represent a snapshot of the median of one year's data, and may not reflect current conditions at the stations. Values shown in bold font exceed recommended values for chemistry optimization; values highlighted in green meet recommended values.

Reactor water soluble Co-60 at all the BWRs with high reactor water zinc exceeds the recommended value of $<5\text{E-}5 \mu\text{Ci/ml}$. However, all plants met the goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ (Exelon has a fleet goal of $<1\text{E-}5 \mu\text{Ci/ml/ppb}$.) for the reactor water soluble Co-60 to soluble zinc ratio, although nine BWRs with NMCA did so with feedwater zinc concentrations greater than 0.4 ppb. Some BWRs have obtained concurrence from fuel vendors to operate with feedwater zinc concentrations greater than 0.4 ppb. None of the plants have high feedwater iron, and the zinc concentration factor varies between 20 and about 40.

The data from these plants indicate that goals for fuel reliability and shutdown radiation field control may have to be balanced based on site-specific conditions. As discussed in Chapter 5, the correlation between Co-60(s)/Zn(s) and low dose rates is not as good during the third+ cycle after NMCA compared with the first two cycles, and consideration could be given to lower zinc injection rates during these cycles.

Table 4-1
BWR chemistry parameters at high (>10 ppb) reactor water zinc plants (latest median values)

Plant	Chemistry Regime	RW Zn ppb	Co-60(s) $\mu\text{Ci/ml}$	FW Fe(t) ppb	FW Zn(t) ppb	RW/FW Zn ppb/ppb	Co-60/Zn $\mu\text{Ci/ml-ppb}$
PER	NMCA	10.20	1.18E-04	0.071	0.368	27.76	1.16E-05
RIB	HWC	10.74	7.78E-05	0.030	0.250	42.96	7.24E-06
CGS	NMCA	10.75	1.98E-04	0.257	0.504	21.33	1.84E-05
PB3	NMCA	11.30	1.49E-04	0.461	0.560	20.18	1.32E-05
BRU1	HWC	11.55	7.02E-05	0.306	0.358	32.26	6.08E-06
DUA	NMCA	11.60	6.87E-05	0.573	0.341	34.02	5.92E-06
BRF2	NMCA	11.63	1.36E-04	0.129	0.376	30.92	1.17E-05
BRF1	NMCA	12.12	1.02E-04	0.211	0.372	32.58	8.37E-06
LAS1	NMCA	12.30	1.48E-04	0.060	0.570	21.58	1.20E-05
CNS	NMCA	12.70	2.12E-04	0.400	0.335	37.91	1.67E-05
BRF3	NMCA	13.03	1.51E-04	0.268	0.348	37.44	1.16E-05
PB2	NMCA	13.06	1.78E-04	0.463	0.640	20.41	1.36E-05
MON	HWC	14.80	6.51E-05	0.028	0.407	36.36	4.40E-06
BRU2	HWC	15.00	1.98E-04	0.161	0.365	41.10	1.32E-05
LIM1	NMCA	15.10	2.48E-04	0.338	0.470	32.12	1.64E-05
LIM2	NMCA	16.30	2.70E-04	0.294	0.566	28.78	1.66E-05
QUA2	NMCA	16.56	1.33E-04	0.471	0.721	22.96	8.03E-06
QUA1	NMCA	16.92	1.51E-04	0.261	0.629	26.90	8.92E-06
LAS2	NMCA	18.40	3.41E-04	0.950	0.710	25.92	1.85E-05

Fleet reactor water and feedwater zinc trends are shown in Figure 4-5. There has been a consistent upward trend in reactor water zinc concentrations, from 5 ppb in 2000 to almost 10 ppb in 2008. However, the feedwater zinc trend is not consistent with the reactor water zinc trend. Following an increase from 2000 to 2001, fleet median feedwater zinc concentrations decreased from 0.55 ppb in 2001 to 0.36 ppb in 2006, while reactor water zinc increased from 6.8 ppb in 2001 to 8.3 ppb in 2008. A contributing factor is the reduction in feedwater iron in these years, resulting in a higher zinc concentration factor. There is a recent slight upward trend in feedwater zinc from 0.36 ppb in 2006 to 0.40 ppb (11%) in 2008, while reactor water zinc increased from 8.3 to 9.5 ppb (15%) during this same period.

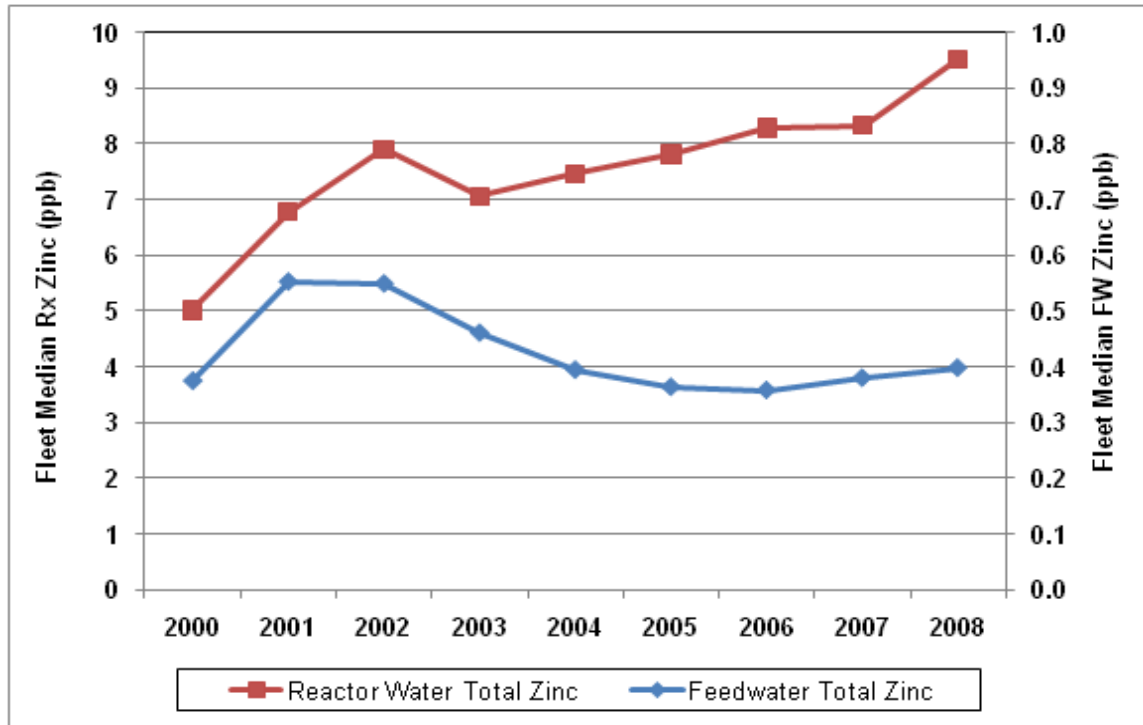


Figure 4-5
BWR fleet zinc trends (2000 – 2008)

Zinc concentration factor (Reactor Zinc/Feedwater Zinc, ZCF) trends are shown in Figure 4-6. In 2000, the percentage of BWRs with ZCF less than 20 was 60 and the average ZCF was 16.3. With the reduction in feedwater iron due to prefilter retrofits and condensate filter septa selection, the percentage of BWRs with a low ZCF has decreased to 27% and the average ZCF has increased to 23. However, as shown in Chapter 3, there is a considerable variation in ZCF among BWRs with similar feedwater iron concentrations. A similar relationship exists between the ZCF and feedwater zinc, as shown in Figure 4-7.

Further analysis was done to determine whether plants with high feedwater iron were responsible for high feedwater zinc, and results are shown in Figure 4-8. For both low (<1 ppb) and high (>1 ppb) feedwater iron plants, the ZCF decreases as feedwater zinc increases. The trend line for the high iron plants is flatter than that of the low iron plants, suggesting more zinc uptake in the insoluble crud in the reactor.

Further analysis of data on a plant by plant basis is needed to develop a zinc injection strategy for balancing fuel reliability and dose control concerns.

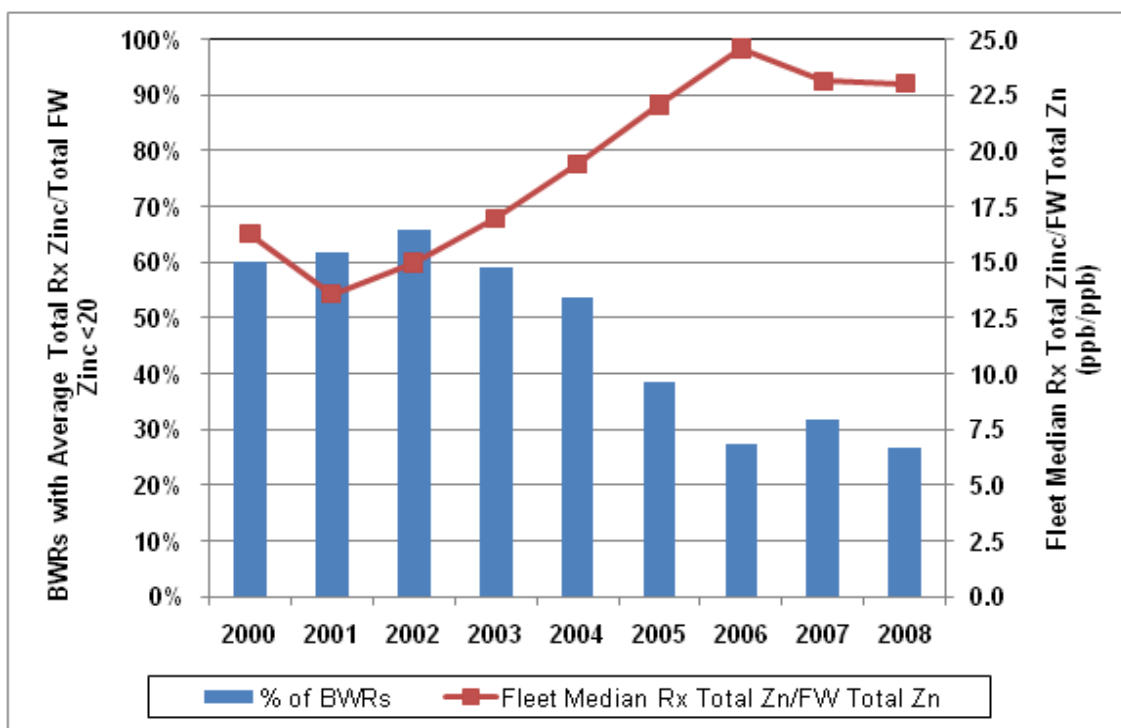


Figure 4-6
BWR fleet zinc concentration factor trends (2000 – 2008)

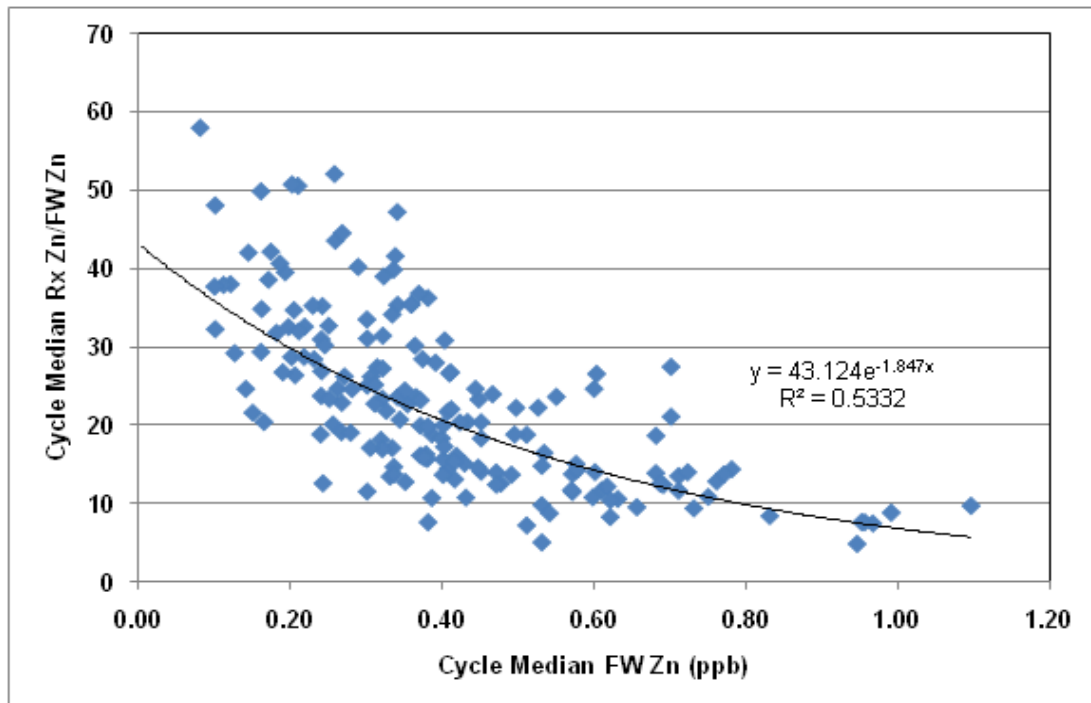


Figure 4-7
Zinc concentration factor vs. feedwater zinc

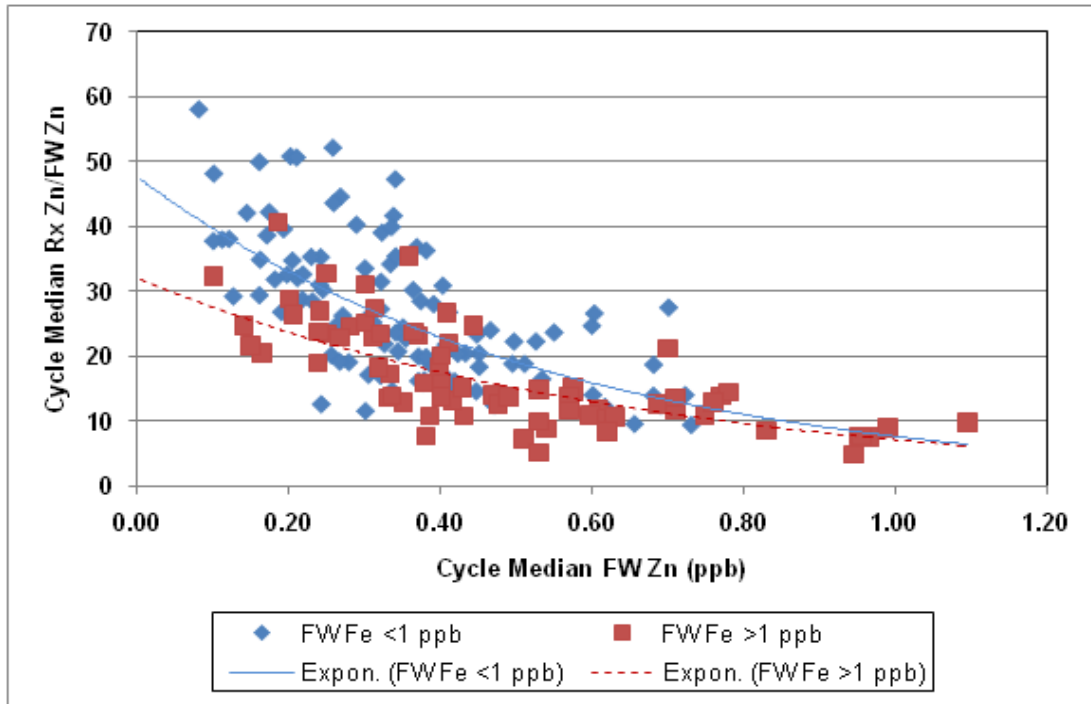


Figure 4-8
Zinc concentration factor vs. feedwater zinc for low and high feedwater iron plants

Recent Fuel Failures

Available information on recent fuel failures (2004 on) is summarized in Table 4-2. Updates were not available from all stations. At the time of this report preparation, no new BWR fuel failures have been identified with water chemistry as the root cause.

The most recent failures that have been attributed to corrosion were detected during five cycles at four BWRs: Browns Ferry 2 and 3, River Bend, and Vermont Yankee. The corrosion failures are of interest because of the potential influence of water chemistry. Detailed information on the fuel failures was provided in earlier versions of this report [3, 4].

Table 4-2
Reported BWR fuel failures

Station	Cycle	BOC	EOC	Date of Failure	Cycle for Failed Fuel	Cause of Failure
BRF3	12	Mar-04	Mar-06	Jul-04 Unknown	Second First	PCI-SCC Debris
BRU1	15	Mar-04	Mar-06	Unknown	Not inspected	Not inspected
BRU2	17	Mar-03	Mar-05	Jul-04	First and Second	Debris
CNS	23	Feb-05	Oct-06	Mar-06	Second	Debris
CNS	25	Apr-08	in progress	Jan-09		
FIT	18	Nov-06	Sep-08	Jan-08		Likely debris
GGNS	15	Oct-05	Mar-07	Oct-05	Third	PCI-SCC
HCNS	14	May-06	Oct-07	Mar-07	Unknown	Unknown
KS1	19	Apr-06	Sep-07	Sep-06 Aug-07	Third Second	Unknown Unknown
KS2	18	Dec-05	Apr-07	Dec-05 Jun-06 Jun-06	Third Second Second	Unknown Perhaps PCI Perhaps PCI
LAS1	12	Mar-06	Feb-08	Jul-07	Unknown	Unknown
LAS2	12	Mar-07	Feb-09	Aug-08	Unknown	Unknown
LIM1	11	Mar-04	Mar-06	Jan-06	First	Debris
MON	24	Apr-07	Mar-09	Aug-07	Unknown	Unknown
NMP1	17	Apr-05	Mar-07	Jun-06	Third	Preliminary cause is debris
NMP2	10	Apr-04	Mar-06	Nov-04	Second	Debris
NMP2	11	Apr-06	Mar-08	Aug-07	Unknown	Unknown
PIL	16	May-05	Apr-07	Oct-05 Jan-07	Unknown	Unknown
QUA2	18	Mar-04	Mar-06	Mar-04	Second	Likely manufacturing defect
RIB	13	Nov-04	Apr-06	Oct-05	Second First	PCI-SCC Unknown

Fuel Crud Database

The BWR Fuel Crud Database was started in 2008 to provide a single source of information on fuel inspection results and chemistry parameters during the operating cycles for the inspected fuel. Currently, information is included for the following plant cycles:

- Browns Ferry 2, discharged at EOC 10 – 12
- Columbia, discharged at EOC 16 - 17
- Duane Arnold, discharged at EOC 13 – 14
- LaSalle 2, discharged at EOC 9
- Mühleberg, discharged at EOC 31 – 34
- Peach Bottom 2, discharged at EOC 12 – 13
- Perry, discharged at EOC 8 – 10
- Quad Cities 2, discharged at EOC 18
- River Bend, discharged at EOC 11
- Vermont Yankee, discharged at EOC 19 – 22

Although there is limited data yet available in the database, preliminary analysis suggests several possible correlations. The specific activity (Curies Co-60 per gram of cobalt) of brushed samples is plotted against cycle average feedwater iron in Figure 4-9. There is a good correlation of the results, indicating higher specific activity at plants with higher feedwater iron. A similar plot for scraped samples is shown in Figure 4-10. When all data were included, there were two outlier results; when these two results were eliminated, the correlation improved significantly. Similar plots vs. exposure time of the fuel indicated that the specific activity increases linearly with fuel life, as would be expected.

The ratio of cobalt mass in the scraped results to specific activity in the brushed results is plotted against cycle average feedwater iron in Figure 4-11. Although there is no correlation, the data suggest that as feedwater iron increases, the ratio decreases. Since the brushed results represent the more loosely adherent crud layer, a decreased ratio indicates that the crud layer is more loosely adherent, and thus cobalt is more likely to be released during shutdown evolutions, potentially contributing to outage radiation exposure.

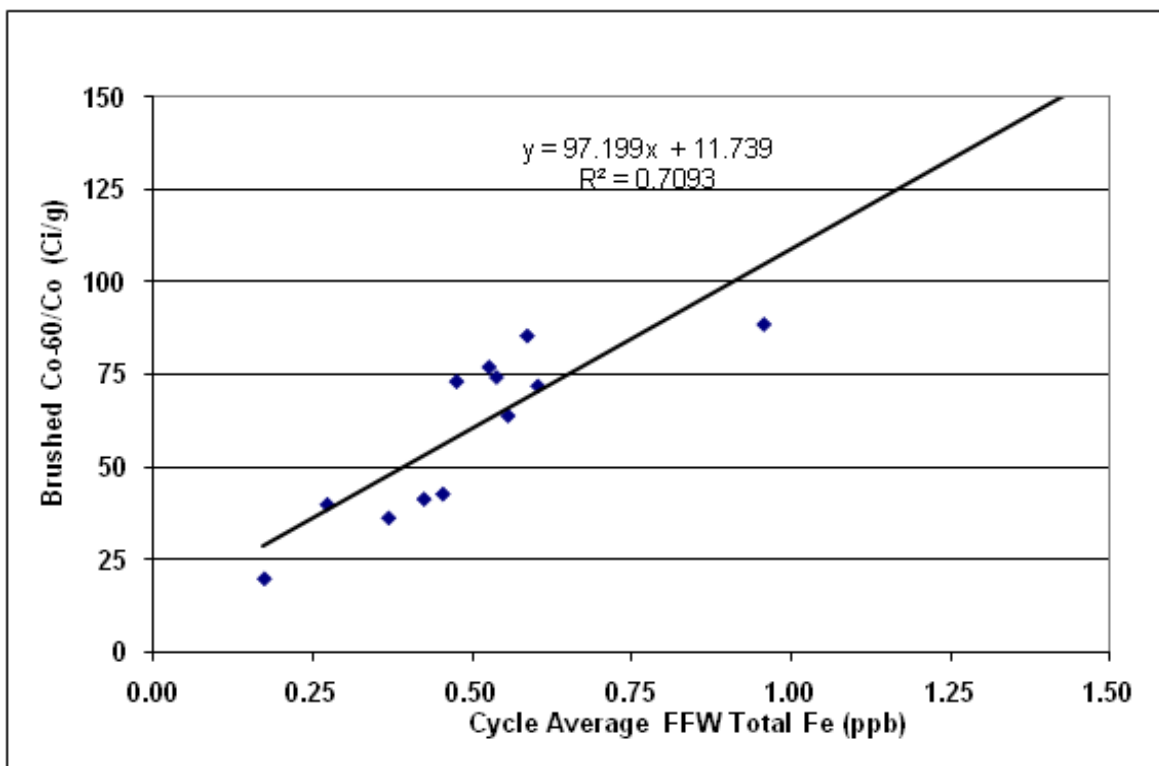


Figure 4-9
Brushed specific activity vs. feedwater iron

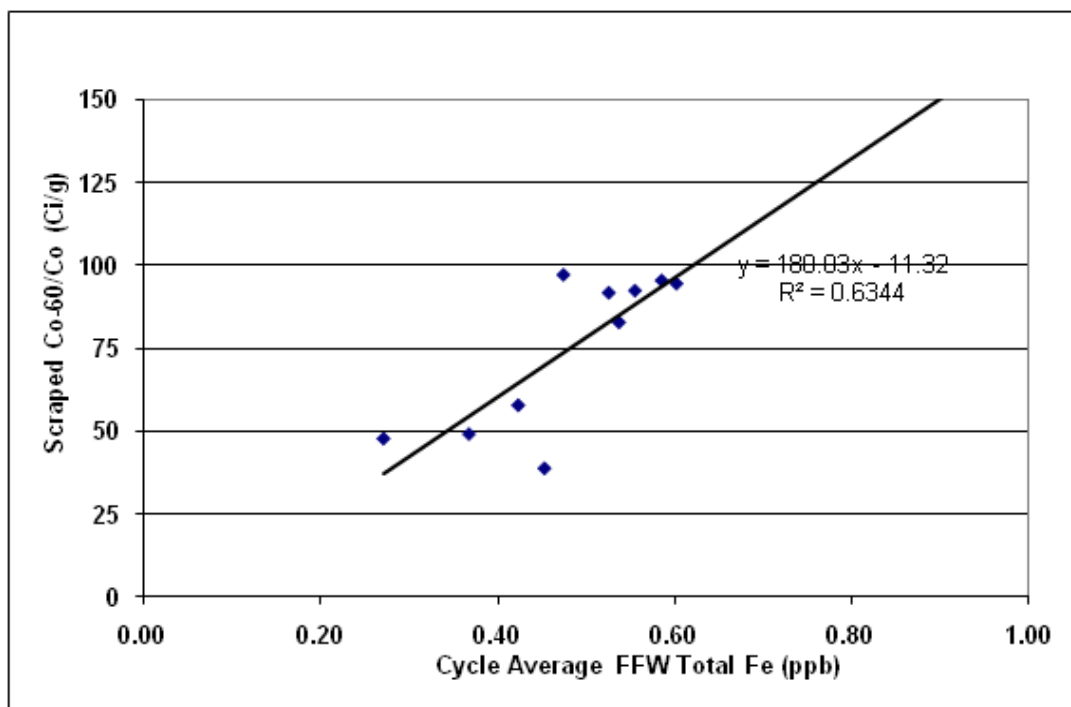


Figure 4-10
Scraped specific activity vs. feedwater iron (two outliers not included)

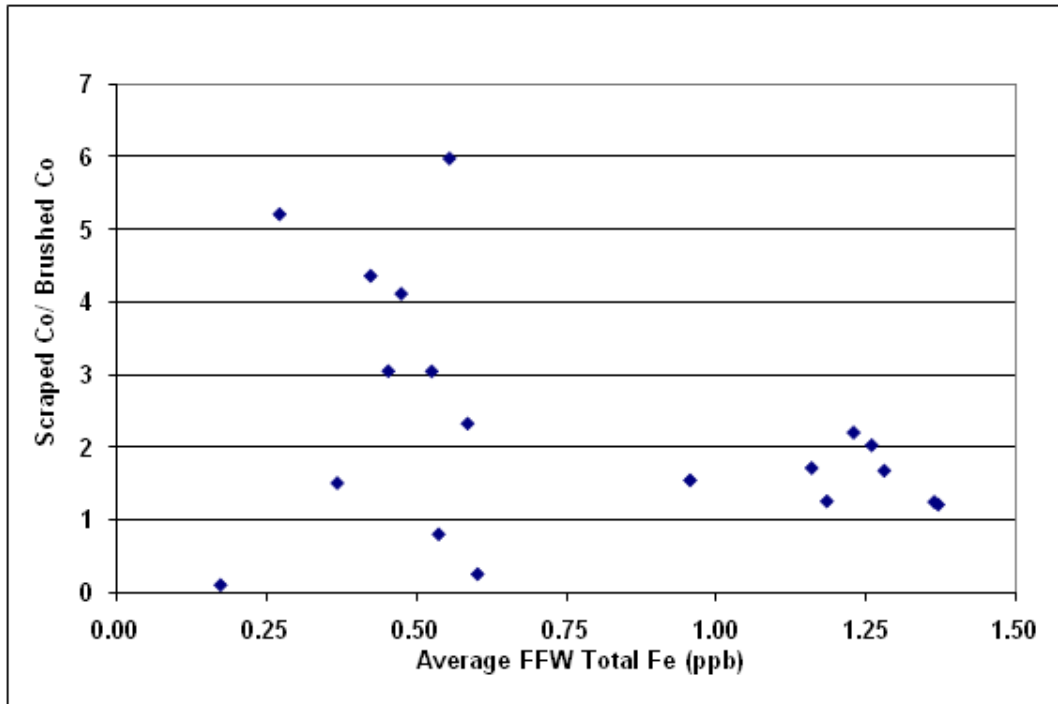


Figure 4-11
Ratio of scraped cobalt to brushed cobalt vs. feedwater iron

Conclusion

BWRs have made significant progress in iron and copper control, contributing to fuel reliability assurance. In recent years, the trend has been toward higher feedwater (and reactor water) zinc concentrations to achieve the reactor water Co-60(s)/Zn(s) goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ for radiation field control. A comprehensive review of zinc injection strategies and resultant dose rate and fuel reliability impacts is planned for 2009 – 2010.

References

1. *BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision*. EPRI, Palo Alto, CA: 2008. 1016579.
2. *Fuel Reliability Guidelines: BWR Fuel Cladding Crud and Corrosion*. EPRI, Palo Alto, CA: 2008. 1015451.
3. *Boiling Water Reactor Chemistry Performance Monitoring Update – 2007 Edition*. EPRI, Palo Alto, CA: 2007. 1016102.
4. *Boiling Water Reactor Chemistry Performance Monitoring Report - 2005 Edition*. EPRI, Palo Alto, CA: 2005. 1009932.

5

CHEMISTRY INFLUENCE ON DRYWELL RADIATION DOSE RATES

Monitoring of Drywell Radiation Dose Rates

BRAC Monitoring Program and Practices

The BWR fixed point survey program, commonly referred to as BRAC (*BWR Radiation Level Assessment and Control*), is discussed in General Electric document NEDC-12688, which was issued in 1977 based on work sponsored jointly by General Electric and EPRI [1]. The intent of the BRAC program is to establish 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 program specifies locations, frequency, timing, and instrumentation for periodic fixed-point radiation dose rate surveys of BWR primary system components in order to provide consistent and comparable data.

The BRAC average values used throughout this report are the average of the recirculation suction and discharge contact dose rate readings taken in the vertical piping runs, usually with a shielded directional probe. Surveys should be conducted with the component in its normal configuration; for example, with any insulation in place and liquid-filled. The BRAC program does not specify a distance between the target survey point and the system components (e.g., a valve in the pipe) nor does it recommend a length for straight run of pipe. It only specifies that each unit should be consistent with its selected points.

Compression of outage schedules has resulted in many surveys being performed less than one week after reactor shutdown. In this case, short-lived isotopes may not yet have decayed, resulting in slightly higher values than those that would be obtained at a later time. If a plant experienced a fuel failure during the cycle, 7 to 14 days may be insufficient to eliminate the contribution from the additional iodine-131. Most plants achieve at least a 2-day interval for decay of short-lived isotopes before obtaining BRAC measurements.

Differences in plant design, access platforms, use of permanent shielding, and other plant- and outage-specific conditions may also contribute to inconsistency in the exact locations of the survey points. In addition, surveys may be conducted when systems are drained or with insulation removed. Many units have changed insulation types over the years, which would change the effective standoff distance or the radiation shielding value of the insulation. Performing the survey with systems drained will most likely result in higher readings than if the system were full.

BRAC Monitoring Results

The most recent reported BRAC point average dose rates for the BWRs participating in the BWR Chemistry Monitoring Program, as of July 2009, are shown in Figure 5-1. Data points are differentiated by the prevailing chemistry regime during the cycle prior to the dose rate measurements.

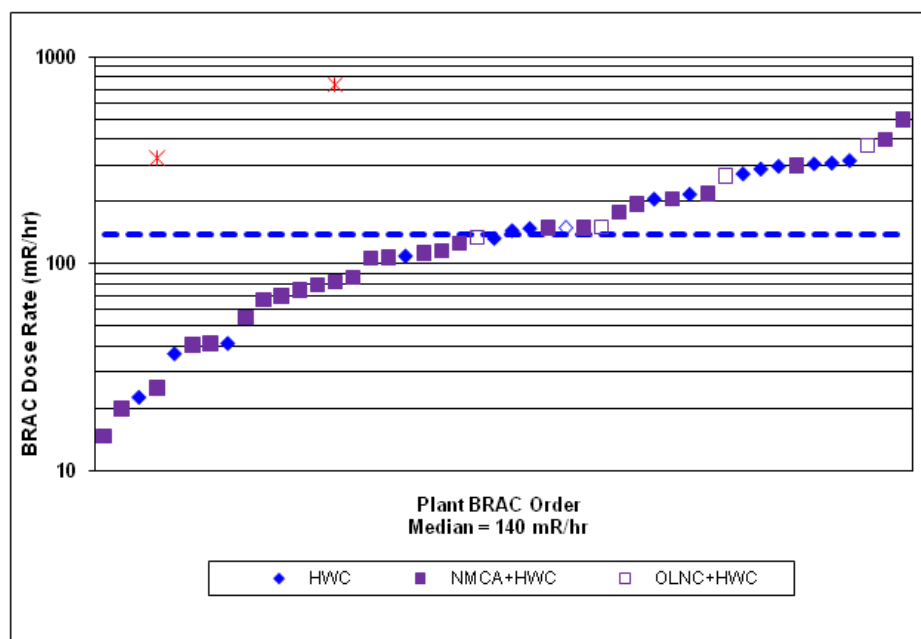


Figure 5-1
Most recent BRAC average dose rates for BWRs designated by chemistry regime at time of measurement

The pre-decon BRAC average is also plotted if a chemical decontamination of the reactor recirculation loop was performed in the outage.

The distribution of the most recent reported BRAC results by quartile is provided in Figure 5-2. The results indicate a significantly wider variation in BRAC dose rates among the plants with dose rates in the highest quartile compared to those of the lowest three quartiles.

The variation in the individual BRAC point measurements is shown in Figure 5-3. For most BWRs, the A and B Suction and Discharge points were used. For Nine Mile Point 1 and Oyster Creek, BWR 2 design with five recirculation loops, the points with the highest and lowest BRAC results were used to calculate the range. There is a much wider range of dose rate values among plants with high dose rates than among plants with low dose rates, indicating that the average BRAC results may be influenced by one loop with higher dose rates. The average BRAC point range for the twenty-three plants with lower dose rates is 35 mR/hr and the average standard deviation is 17 mR/hr. For the twenty-three plants with higher dose rates, the average range is 142 mR/hr and the average standard deviation is 67 mR/hr. For each set of plants, the standard deviation is about 50% of the range. The standard deviation of the individual BRAC points is plotted vs. the average BRAC measure in Figure 5-4. The data indicate higher standard deviations and more scatter as the BRAC dose rate increases.

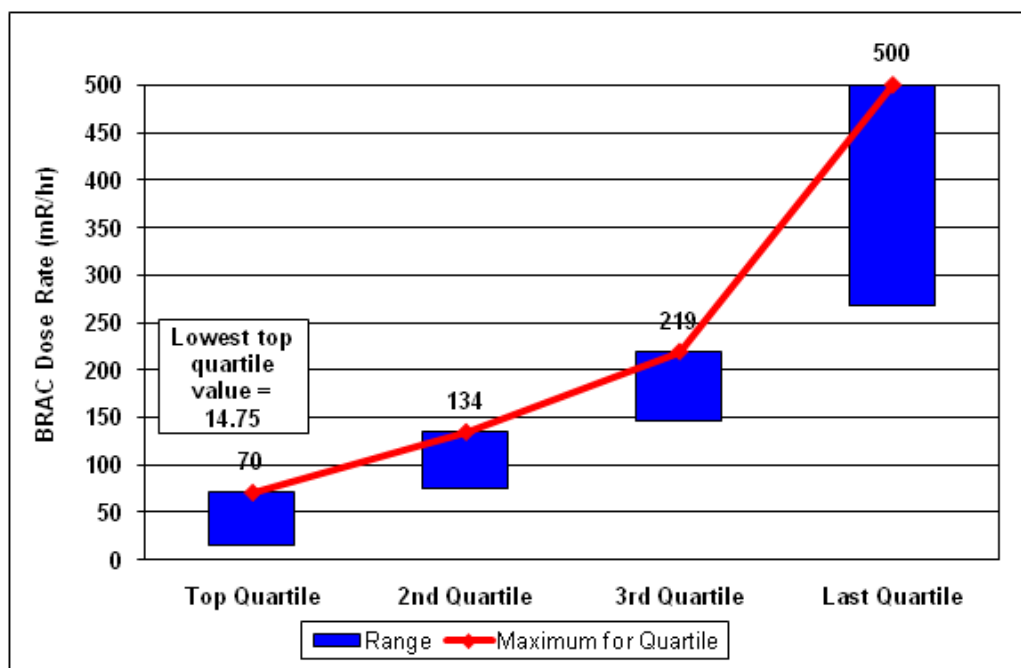


Figure 5-2
Quartile distribution of most recent BRAC average dose rates for BWRs

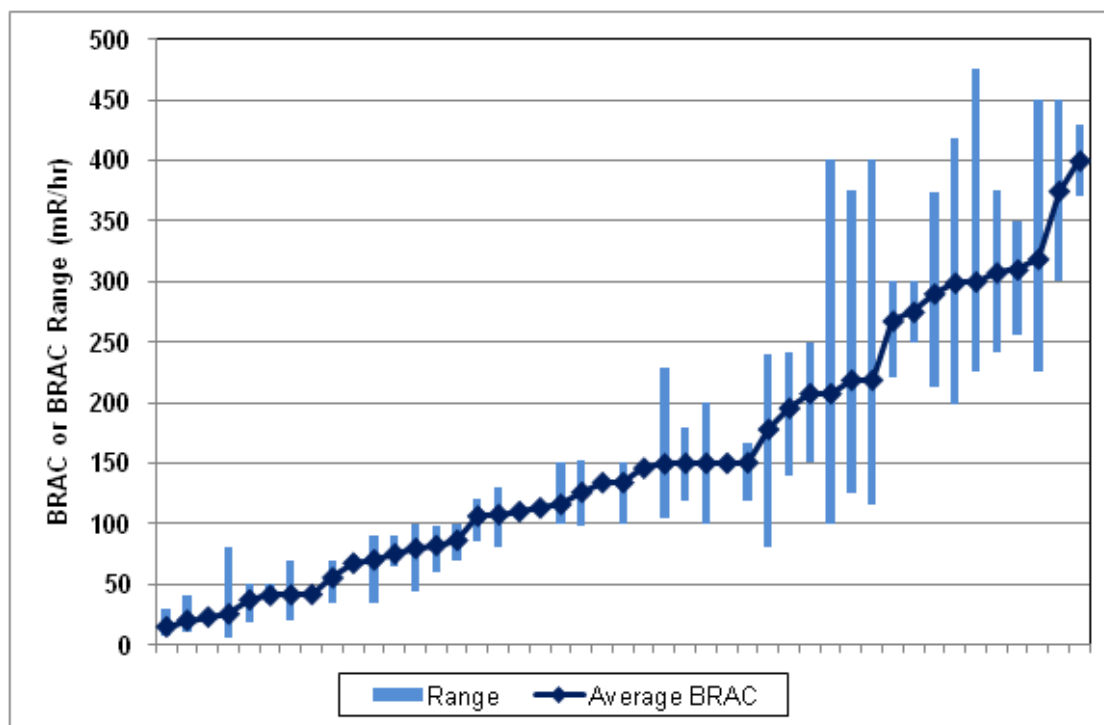


Figure 5-3
Variation in BRAC point measurements (July 2009)

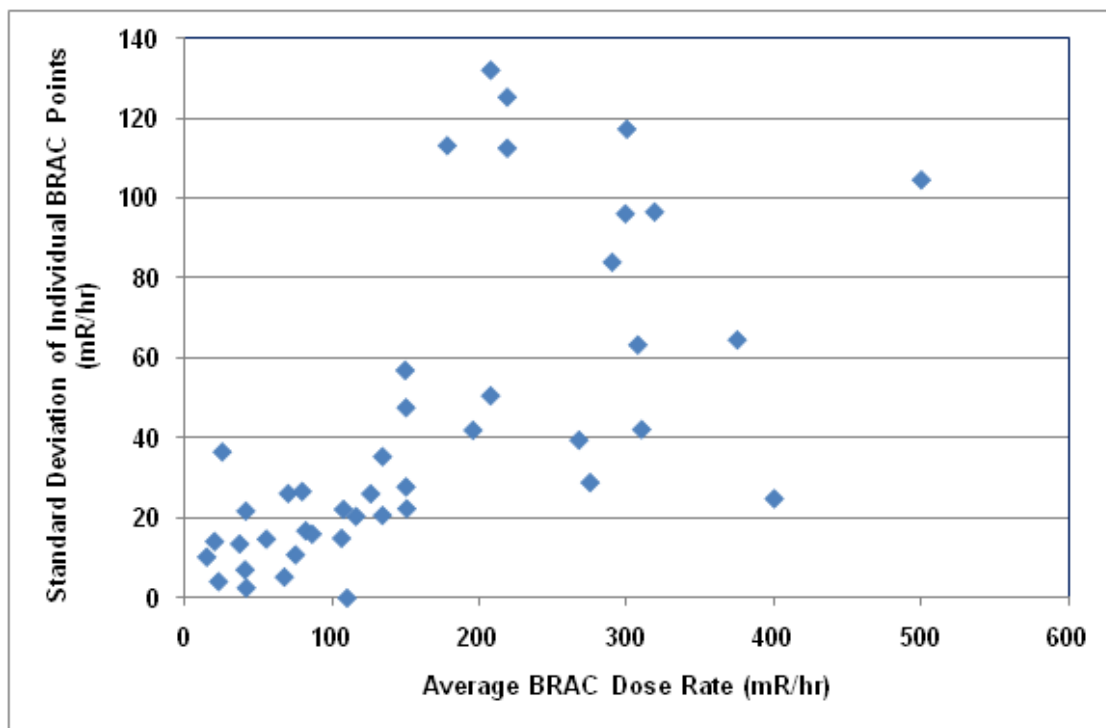


Figure 5-4
Standard deviation of individual BRAC points (July 2009)

The change in the most recently reported BRAC results from the previous results for the forty-six BWRs differentiated by chemistry regime is shown in Figure 5-5. Where applicable, pre-decon dose rates are used. The median change for this data set was -3 mR/hr (about -2%).

A statistical representation of the data in Figure 5-5 is shown in Figure 5-6. Half of HWC plants and 46% of NMCA experienced increased BRAC dose rates, while three of four OLNC plants and one NWC plant experienced lower BRAC dose rates.

The most recent and prior survey results are given in Table 5-1. The date of the last chemical decontamination (or replacement) of the recirculation piping and the chemistry regime in effect prior to the most recent measurement are also provided.

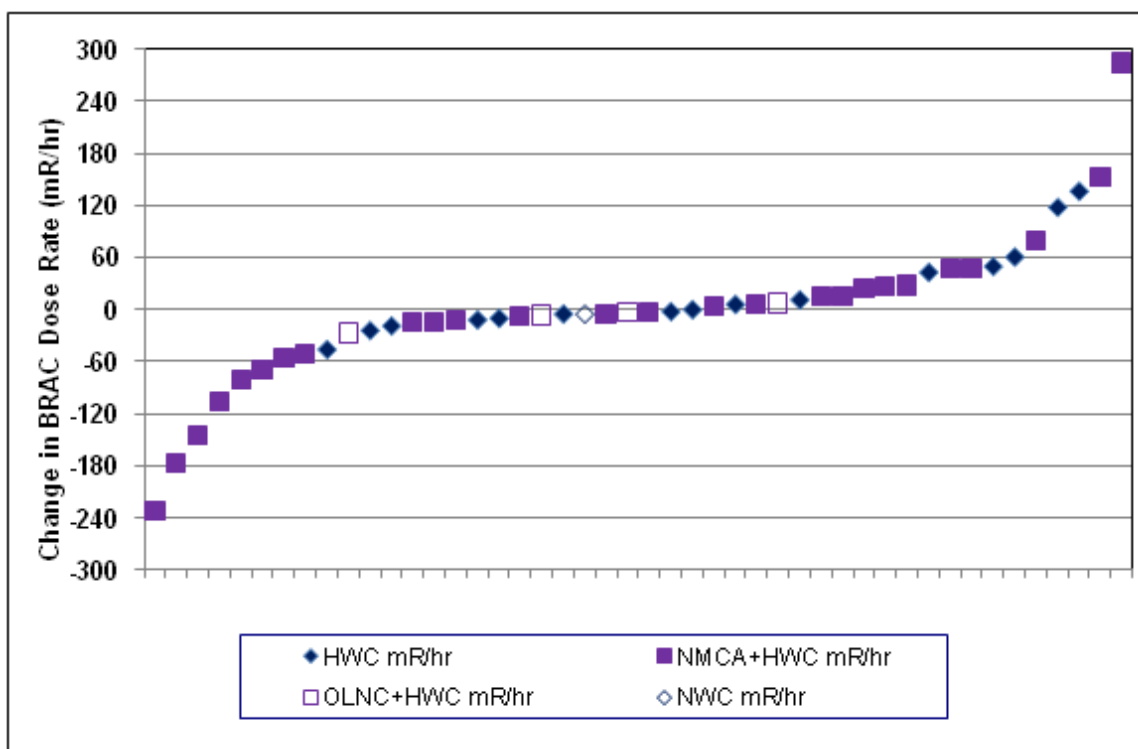


Figure 5-5
Change in most recent BRAC average dose rates for BWRs

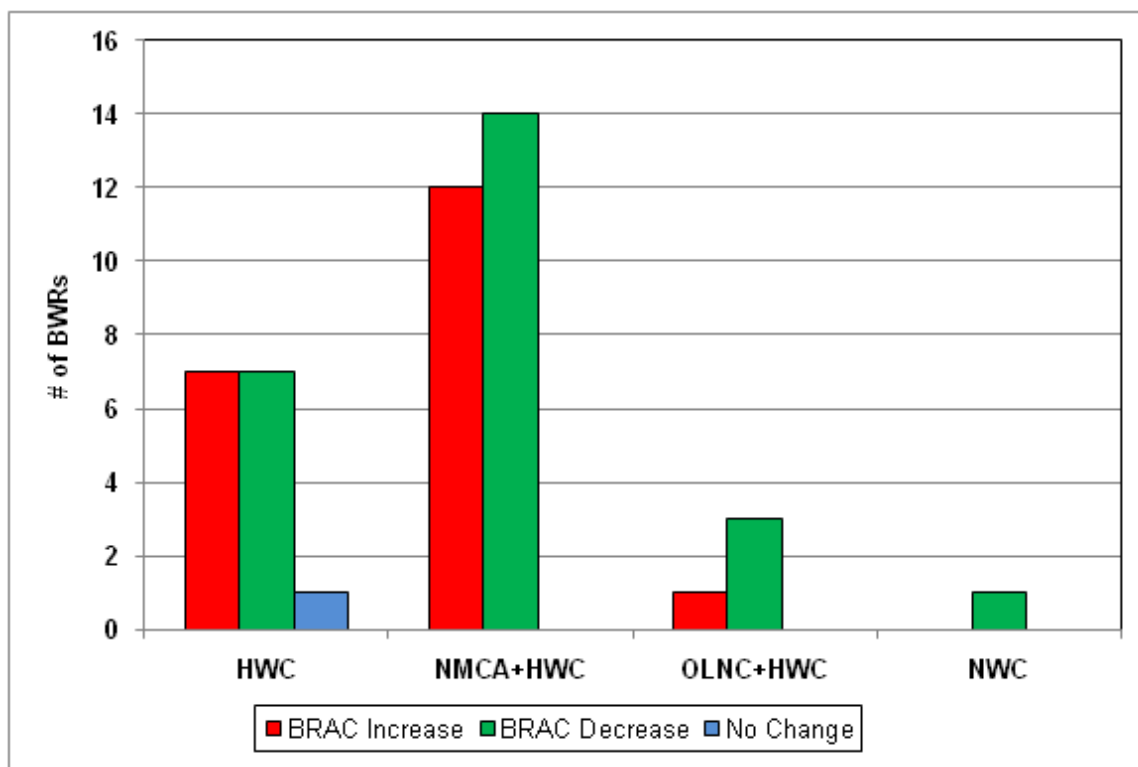


Figure 5-6
BRAC dose rate change (July 2009)

Table 5-1
BWR BRAC averages (July 2009)

Plant	Last Recirc Chem Decon	Most Recent RFO	Most Recent BRAC			Previous BRAC		mR/hr Change	% Change	Pre Decon BRAC (mR/hr)	Chem Regime Prior to Latest BRAC
			Date	BRAC (mR/hr)	RFO or Mid-Cycle	Date	BRAC (mR/hr)				
BRF1	2007	Oct-08	Nov-08	15	RFO	May-07	0	15			NMCA + HWC
BRF2	Feb-07	Apr-09	May-09	113	RFO	Feb-07	34	79	232		NMCA + HWC
BRF3	Mar-08	Mar-08	Mar-08	25	RFO	Mar-06	300	25	8	325	NMCA + HWC
BRU1	1995	Mar-08	Mar-08	319	RFO	Mar-06	338	-19	-6		HWC-M
BRU2	1996	Feb-09	Mar-09	275	RFO	Mar-07	275	0	0		HWC-M
CGS	2007	May-09	May-09	80	RFO	May-07	87	-8	-9		NMCA + HWC
CLI	1993	Jan-08	Jan-08	150	RFO	Feb-06	144	6	4		NMCA + HWC
CNS	1984	Apr-08	Apr-08	219	RFO	Oct-06	171	48	28		NMCA + HWC
COF	2005	Apr-07	May-07	150	RFO	Jun-05	32	118	371		HWC-M
CS1	Feb-01	Oct-08	Oct-08	310	RFO	Mar-07	249	61	24		HWC
CS2	Nov-00	Mar-08	Mar-08	308	RFO	Sep-06	265	43	16		HWC
DRE2	pipe repl 1997	Oct-07	Nov-07	55	RFO	Nov-05	27	28	105		NMCA + HWC
DRE3	1994	Nov-08	Nov-08	41	RFO	Nov-06	96	-55	-57		NMCA + HWC
DUA	1995	Feb-09	Feb-09	208	RFO	Mar-07	210	-3	-1		NMCA + HWC
ENF		Mar-09	Apr-09	37	RFO	Oct-07	83	-46	-55		HWC-M
GGNS	1995	Sep-08	Oct-08	110	RFO	Apr-07	120	-10	-8		HWC-M
HAT1	1996	Feb-08	Feb-08	67	RFO	Feb-06	72	-5	-6		NMCA + HWC

Table 5-1
BWR BRAC averages (July 2009) (continued)

Plant	Last Recirc Chem Decon	Most Recent RFO	Most Recent BRAC			Previous BRAC		mR/hr Change	% Change	Pre Decon BRAC (mR/hr)	Chem Regime Prior to Latest BRAC
			Date	BRAC (mR/hr)	RFO or Mid- Cycle	Date	BRAC (mR/hr)				
HAT2	1984	Feb-09	Feb-09	41	RFO	Feb-07	56	-15	-27		NMCA + HWC
HCNS		Apr-09	Apr-09	75	RFO	Oct-07	88	-13	-14		NMCA + HWC
JAF	1994	Sep-08	Sep-08	116	RFO	Oct-06	89	27	31		NMCA + HWC
KKL	Aug-04	Aug-08	Aug-08	150	RFO	Aug-07	155	-5	-3		NWC
KKM		Aug-08	Aug-08	151	RFO	Aug-07	178	-27	-15		OLNC + HWC
KS1	Sep-01	Mar-09	Mar-09	290	RFO	Sep-07	314	-24	-8		HWC
KS2	Feb-92	Nov-08	Nov-08	299	RFO	Apr-07	293	6	2		HWC
LAG1	1998	Oct-08	Oct-08	400	RFO	Mar-07	247	153	62		NMCA + HWC
LAG2	2000	Apr-09	Apr-09	500	RFO	Oct-07	216	284	131		NMCA + HWC
LAS1	1996	Feb-08	Feb-08	196	RFO	Mar-06	373	-177	-48		NMCA + HWC
LAS2	2005	Jan-09	Jan-09	126	RFO	Mar-07	123	4	3		NMCA + HWC
LIM1		Mar-08	Mar-08	150	RFO	Mar-06	103	48	46		NMCA + HWC
LIM2		Mar-09	Apr-09	86	RFO	Mar-07	168	-81	-49		NMCA + HWC
MON		Mar-09	Apr-09	219	RFO	Apr-07	208	11	5		HWC-M
NMP1	2005	Mar-09	Mar-09	134	RFO	Mar-07	137	-3	-2		OLNC + HWC
NMP2		Mar-08	Apr-08	375	RFO	Mar-06	381	-6	-2		OLNC + HWC
OYC	1991	Nov-08	Nov-08	178	RFO	Oct-06	162	16	10		NMCA + HWC
PB2	pipe repl 1985	Sep-08	Sep-08	108	RFO	Sep-06	253	-145	-57		NMCA + HWC

Table 5-1
BWR BRAC averages (July 2009) (continued)

Plant	Last Recirc Chem Decon	Most Recent RFO	Most Recent BRAC			Previous BRAC		mR/hr Change	% Change	Pre Decon BRAC (mR/hr)	Chem Regime Prior to Latest BRAC
			Date	BRAC (mR/hr)	RFO or Mid- Cycle	Date	BRAC (mR/hr)				
PB3	pipe repl 1988	Sep-07	Sep-07	268	RFO	Oct-05	260	8	3		OLNC + HWC
PER	Feb-09	Feb-09	Feb-09	82	RFO	May-07	965	-232	-24	733	NMCA + HWC
PIL	1997	Apr-09	May-09	300	RFO	Apr-07	406	-106	-26		NMCA + HWC
QUA1	2005	Apr-09	May-09	70	RFO	May-07	84	-14	-16		NMCA + HWC
QUA2	2004	Mar-08	Mar-08	20	RFO	Apr-06	71	-51	-72		NMCA + HWC
RIB	2008	Jan-08	Sep-08	208	mid	Jan-08	71	136	191		HWC-M
RIN1	1997	Oct-07	Sep-08	134	mid	Oct-07	139	-5	-4		HWC-M
SMG	1999	Mar-09	Feb-07	146	RFO	Mar-05	96	50	52		HWC-M
SUS1	2004	Mar-08	Mar-08	23	RFO	Mar-06	25	-2	-9		HWC-M
SUS2	2003	Apr-09	May-09	42	RFO	Mar-07	53	-12	-22		HWC-M
VY	pipe repl 1986	Oct-08	Nov-08	106	RFO	May-07	176	-70	-40		NMCA + HWC

BRAC dose rates differentiated by drains path and BWR type are shown in Figure 5-7 and summarized in Table 5-2. BRAC dose rates for nine of the thirteen BWRs with forward pumped drains are above the fleet median value of 150 mR/hr; the median BRAC value for plants with cascaded drains is 134 mR/hr compared with a median of 208 mR/hr for plants with forward pumped drains. Cobalt source term in the drains may be in part responsible for higher dose rates at plants with forward pumped drains compared to plants with cascaded drains.

The majority of plants with forward pumped drains are of the BWR 5 and 6 design. These BWRs were designed with higher velocities (approximately 40 – 90% higher than BWR 2/3/4 designs) in the reactor recirculation system, which may affect the chemistry environment at the piping surface. For example, the higher velocity could accelerate wear of noble metals from piping surfaces. Of the eight BWR 5s and 6s which have implemented NMCA, six have forward pumped drains and two have cascaded drains. The six BWR 5/6s with forward pumped drains have a median BRAC dose rate of 388 mR/hr compared with a median of 115 mR/hr for the two BWR 5/6s (one BWR 5 and one BWR 6) with cascaded drains. The value for the cascaded plants is biased low because Columbia BRAC dose rates were near 600 mR/hr before a recirculation system chemical decontamination was performed in 2007.

Most of the BWR 2/3/4 design plants implemented HWC prior to NMCA. Most plants of the BWR 5/6 design did not have a long history of HWC before NMCA, and Columbia and Perry started HWC forty and eighteen months, respectively, after NMCA.

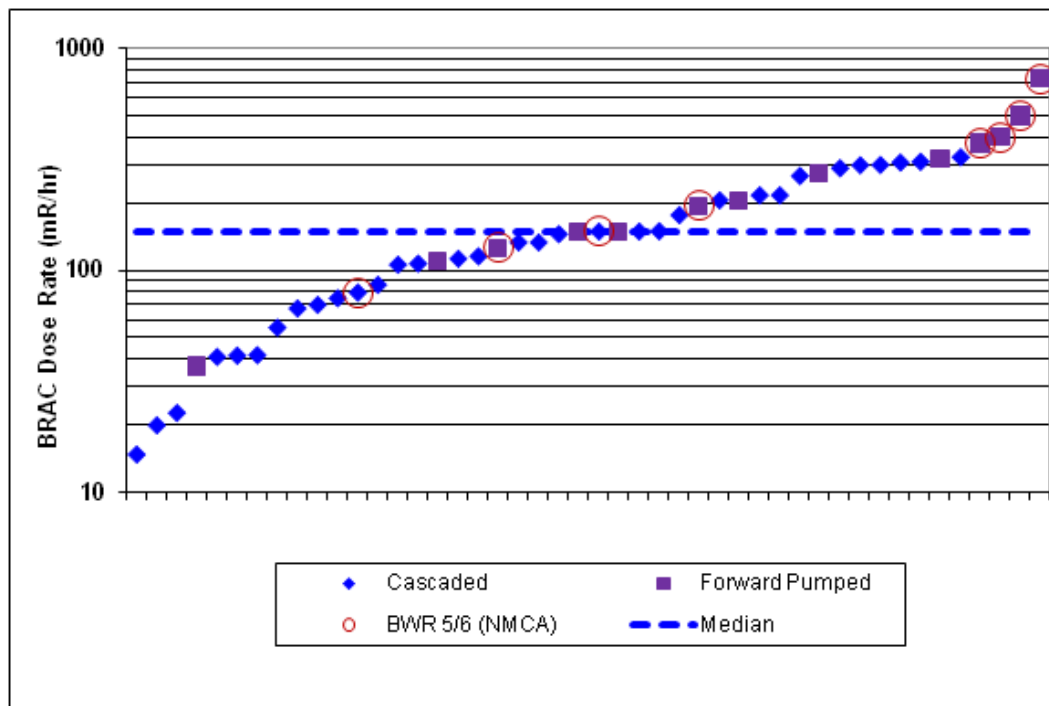


Figure 5-7
BRAC dose rates (July 2009) by drains path and BWR type (pre-decon dose rates used)

Table 5-2
BRAC dose rate summary by drains path and BWR type (pre-decon dose rates used)

	All BWRs		BWR 2/3/4 with NMCA	BWR 5/6 with NMCA		
	Cascaded	Forward Pumped	Cascaded	All	Cascaded	Forward Pumped
# of BWRs	33	13	22	8	2	6
BRAC (mR/hr)						
Median	134	208	110	285	115	388
Average	147	275	130	320	115	388
Minimum	15	37	15	80	80	126
Maximum	325	733	325	733	150	733

Influence of Cobalt-60 and Zinc on BRAC Dose Rates

Incorporation of Co-60 into the oxide film of the reactor recirculation piping is the main source of drywell shutdown radiation dose rates. Co-60 has a half-life of 5.27 years and accounts for 70% or more of the measured drywell dose rates. Co-60 is produced from the neutron activation of naturally occurring Co-59. Stellite[™] hard facing material, which contains approximately 60% cobalt, is a significant source of Co-59 in BWRs and was originally used for its wear resistant properties in primary, feedwater, and balance-of-plant system components. Mn-54, Cr-51, Co-58, Fe-59, and Zn-65 are other typical activated corrosion products that contribute to a lesser extent to BWR radiation dose rates.

Data correlations have shown that the higher the concentration of soluble Co-60 in the reactor coolant, the greater the Co-60 incorporation into the piping oxide film, consequently leading to higher dose rates. The oxide restructuring, from the Fe_2O_3 form to the Fe_3O_4 spinel form, which occurs during the transition from NWC to HWC or from HWC-M to NMCA+HWC, results in an increase in both insoluble and soluble reactor water corrosion products in the coolant. Since Co-60 and zinc compete for sites in the spinel, maintaining a sufficiently high zinc concentration in the coolant (through DZO injection) favors zinc incorporation into the piping oxide film instead of Co-60. Empirical data correlations based on results from twenty plants in the first cycle after NMCA show that maintaining the Co-60(s) to Zn(s) ratio $<2 \times 10^{-5} \mu\text{Ci/ml/ppb}$ in the reactor coolant under these conditions minimizes shutdown dose rates [2]. In these correlations, soluble Co-60 is that fraction of the total Co-60 that passes through a 0.45-micron membrane filter, and insoluble Co-60 is the fraction that does not pass through the membrane.

Higher iron input to the reactor coolant requires a higher zinc injection rate to produce a sufficient residual to maintain the Co-60(s) to Zn(s) target ratio. Higher iron and zinc feed results in a greater concern for a thicker layer of tenacious crud buildup on the fuel, in addition to higher DZO usage. In addition, when the feedwater iron source is mainly from iron in the condensate pump discharge stream that is not removed by the condensate polishing system, cobalt associated with this iron source from the corrosion and wear of plant materials in the flow path to the

condenser can represent a significant cobalt source term. Therefore, low feedwater iron is also beneficial for radiation dose control in a reducing chemistry environment [3], as is cobalt source term reduction through replacement of Stellite™-containing control rod blades and valves.

BWRVIP-190 Summary

Chapter 3 of BWRVIP-190 presents detailed data and analysis related to shutdown dose rates. Significant findings in BWRVIP-190 are summarized below [2].

HWC-M Plants

- HWC-M Plants fall into two distinct groups: those that are able to establish ECP values close to the hydrogen redox potential (-450 to -500 MV(SHE)) and those that can establish ECP less than -230 mV (SHE) but significantly above the hydrogen redox potential. Dose rate behavior in the first group (Group 1) is similar to that of NMCA plants that maintain a low Co-60(s) to Zn(s) ratio. The second group of plants (Group 2) has significantly higher BRAC dose rates, similar to normal water chemistry plants.
- Reactor coolant Co-60(s)/Zn(s) $< 2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ is now a good practice recommendation for HWC-M plants in Table 6-5b.

NMCA Plants

- Both soluble and insoluble Co-60 will increase in most plants during the first post-NMCA cycle.
- BWRs that establish and maintain reactor water Co-60(s)/Zn(s) less than $2\text{E-}5$ $\mu\text{Ci/ml/ppb}$ immediately after NMCA can expect low BRAC dose rates for at least two to four cycles. The above ratio should be established as soon as possible after NMCA to be most effective, and a chemical decontamination prior to the next NMCA may be required to achieve lower dose rates.
- BWRs that do not establish and maintain a low reactor water Co-60(s) to Zn(s) ratio immediately after NMCA will have elevated BRAC dose rates but later establishing a low ratio should limit further increase.
- It is preferable to operate in the lower end of range of the feedwater hydrogen injection rate that assures a molar ratio > 3 (usually 0.15 – 0.25 ppm feedwater hydrogen).

Copper Effect

The presence of greater than 1 ppb of copper in reactor water at HWC-M plants reduces or eliminates the effectiveness of feedwater hydrogen addition in establishing protective ECP, and may also have a negative effect on BRAC dose rates at NMCA plants [2]. Plants with reactor water copper > 1 ppb may not achieve low BRAC dose rates even when maintaining reasonably low reactor water Co-60(s)/Zn(s).

Influence of Feedwater Iron

For a given plant, with lower feedwater iron, less DZO is required to meet the reactor water Co-60(s)/Zn(s) goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$. Although increased soluble Co-60 may occur with a significant reduction in feedwater iron, the effect is more than offset by the lower Co-60(s) to Zn(s) ratio if feedwater zinc injection remains constant.

BWR Dose Rate Experience

The Boiling Water Reactor Chemistry Performance Monitoring Report – 2007 Edition [4] updated the relationship between drywell dose rates and a number of chemistry parameters and ratios using the large quantity of data collected since the inception of the BWR Chemistry Monitoring Database. Additional data and analysis are presented here.

HWC-M Plants

BWRVIP-190 [2] discusses the recent dose rate behavior of plants on HWC-M. As shown in Figure 5-8, there are two groups of plants: Group 1 (Hope Creek, Susquehanna 1 and 2, Fermi 2, Grand Gulf in 2008), with low dose rates, and Group 2 (Brunswick 1 and 2, Cofrentes, Grand Gulf, Monticello, Pilgrim, River Bend), with high dose rates. As a rule, the BRAC dose rates at Group 2 plants are higher for the same reactor coolant Co-60(s)/Zn(s). It is thought that a difference in ECP response is responsible for the difference in dose rates between the two groups of plants [2]. For the data set shown in Figure 5-8, there is a weak correlation between BRAC dose rates and Co-60(s)/Zn(s) but no correlation is apparent for the Group 2 plants. In addition, the range of BRAC dose rates is narrower for the Group 1 plants compared with the Group 2 plants.

Increased hydrogen concentrations may be able to drive a plant's average BRAC dose rate from the Group 2 to the Group 1 category [2]. At Grand Gulf, the hydrogen injection rate was increased from 74 scfm to 98 scfm (1.9 ppm feedwater hydrogen) in 2007. The most recent BRAC dose rate in September 2008 was 91 mR/hr, a decrease of almost 50% from the value of 180 mR/hr in 2005, and almost 70% lower than the value of 293 mR/hr in 2004.

The relationship between feedwater zinc and Co-60(s)/Zn(s) at HWC-M plants is shown in Figure 5-9. Ten of thirteen Group 1 plant cycles and thirteen of twenty Group 2 plant cycles met the Co-60(s)/Zn(s) goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ with a cycle median feedwater zinc concentration less than or near 0.4 ppb, the maximum recommended value in BWRVIP-190. For the twenty-five cycles beginning in 2001 through 2005, 32% of plants that met the EPRI reactor water Co-60(s)/Zn(s) goal exceeded the feedwater zinc goal of 0.4 ppb. For the eight plant cycles beginning in 2006 through 2008, all BWRs met both the Co-60(s)/Zn(s) goal and the feedwater zinc goal.

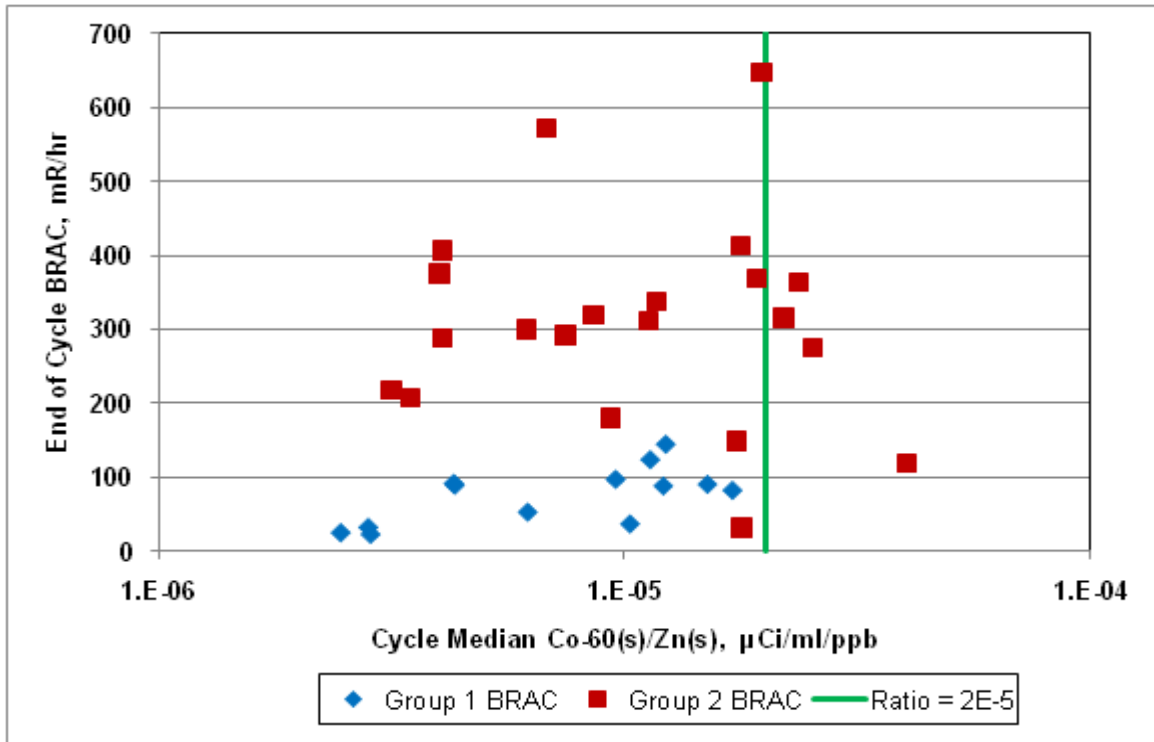


Figure 5-8
BRAC vs. soluble Co-60 to soluble Zn ratio for HWC-M plants

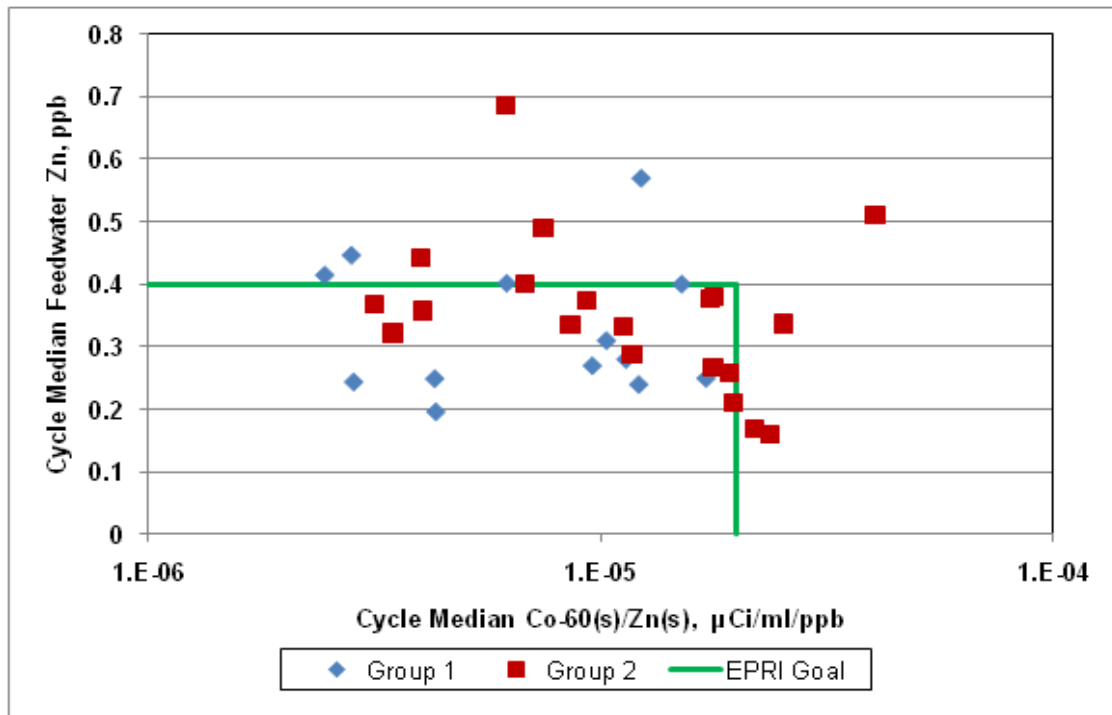


Figure 5-9
Feedwater zinc vs. soluble Co-60 to soluble Zn ratio for HWC-M plants

NMCA Plants

As discussed in Chapter 2, thirty BWRs have performed NMCA as of September 2009, and twenty of these have performed at least one reapplication. Data from over one hundred fuel cycles at these plants were used to develop the correlations presented below.

The relationship between end of cycle BRAC and reactor water soluble Co-60 is shown in Figure 5-10. While there is no apparent correlation, it is noteworthy that all BWRs with cycle median Co-60(s) less than the EPRI good practice value of $5\text{E-}5 \mu\text{Ci/ml}$ experienced BRAC dose rates less than 200 mR/hr. As soluble Co-60 increases above $1\text{E-}4 \mu\text{Ci/ml}$, the percentage of plants with BRAC dose rates less than 200 mR/hr decreased significantly. A BWR with low reactor water soluble Co-60 can meet the reactor water Co-60(s)/Zn(s) goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ with lower feedwater zinc concentrations.

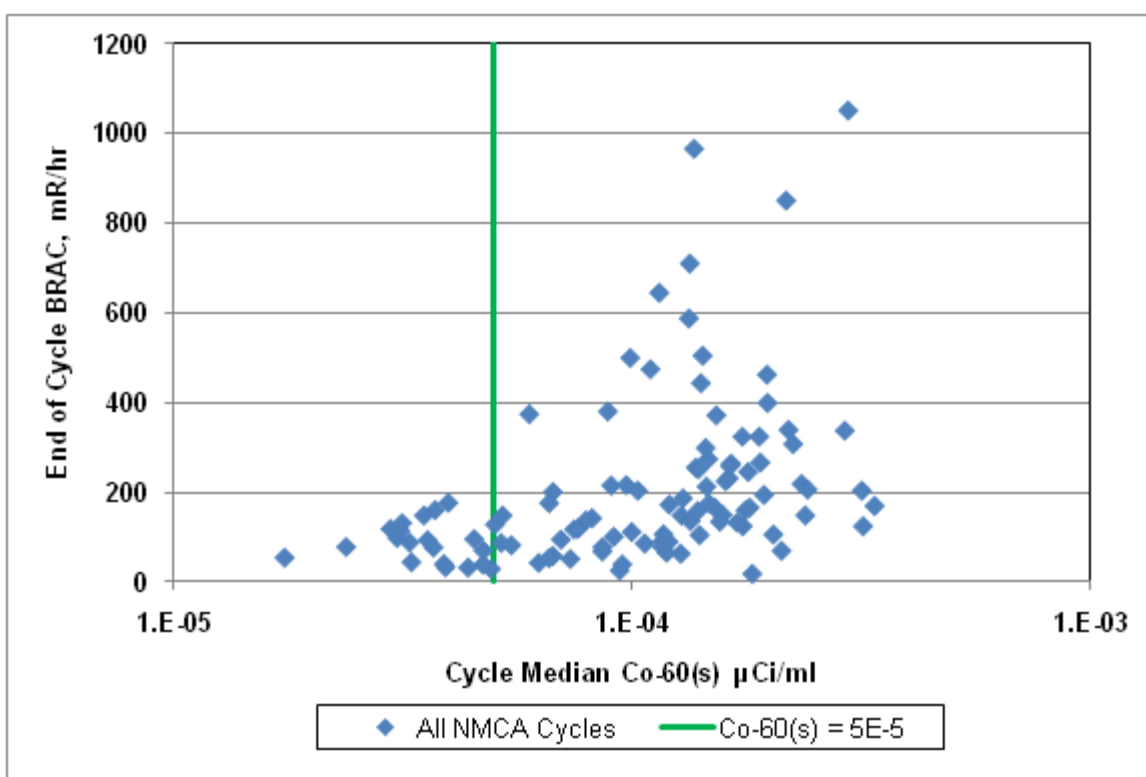


Figure 5-10
BRAC vs. cycle median reactor water soluble Co-60 for NMCA plants (all cycles)

BRAC dose rates are plotted against cycle median reactor water Co-60(s)/Zn(s) in Figure 5-11. The data indicate a weak correlation (note that the x-axis scale is logarithmic). Average BRAC dose rates were less than 200 mR/hr for all BWR cycles when Co-60(s)/Zn(s) was less than $1\text{E-}5 \mu\text{Ci/ml/ppb}$, and all BRAC values less than 100 mR/hr occurred when Co-60(s)/Zn(s) was less than the goal of $2\text{E-}5 \mu\text{Ci/ml/ppb}$.

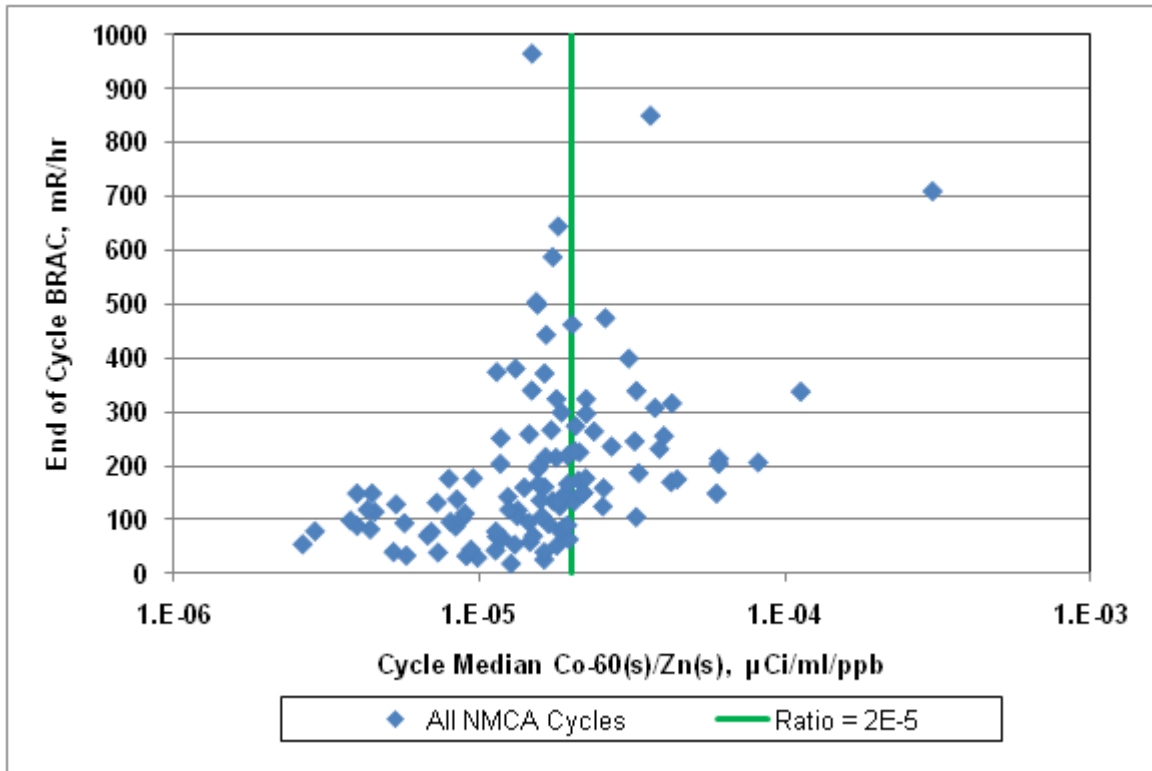


Figure 5-11
BRAC vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (all cycles)

The relationship between feedwater zinc and Co-60(s)/Zn(s) at NMCA plants is shown in Figure 5-12. Thirty-six of the seventy-eight (46%) BWR cycles with median Co-60(s)/Zn(s) less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$ achieved the ratio with a median feedwater zinc concentration less than 0.4 ppb. Seventeen of the twenty-seven (63%) BWR cycles with median Co-60(s)/Zn(s) less than $1\text{E-}5 \mu\text{Ci/ml/ppb}$ achieved the ratio with a median feedwater zinc concentration less than 0.4 ppb.

The percentage of BWRs with NMCA meeting the EPRI goals for reactor water Co-60(s)/Zn(s) and feedwater zinc is shown in Figure 5-13. For cycles beginning in 2000 – 2003, about 52% of BWR cycles met EPRI goals compared to about 92% for cycles beginning in 2004 – 2007.

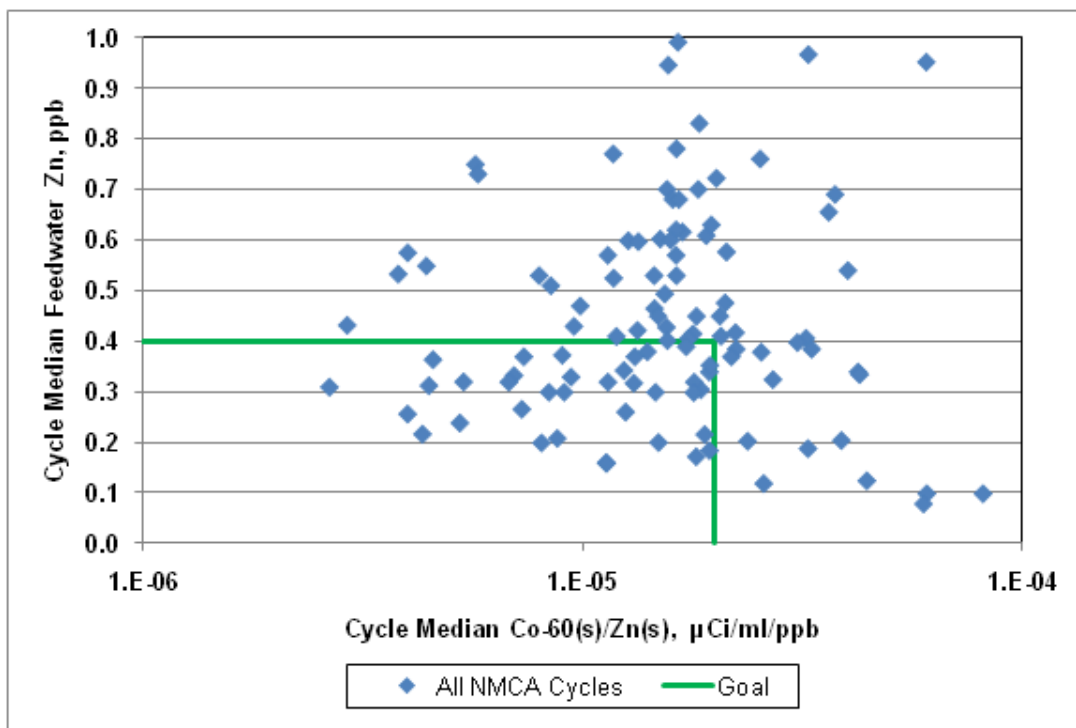


Figure 5-12
Feedwater Zinc vs. reactor water soluble Co-60 to soluble Zn ratio for NMCA plants (all cycles)

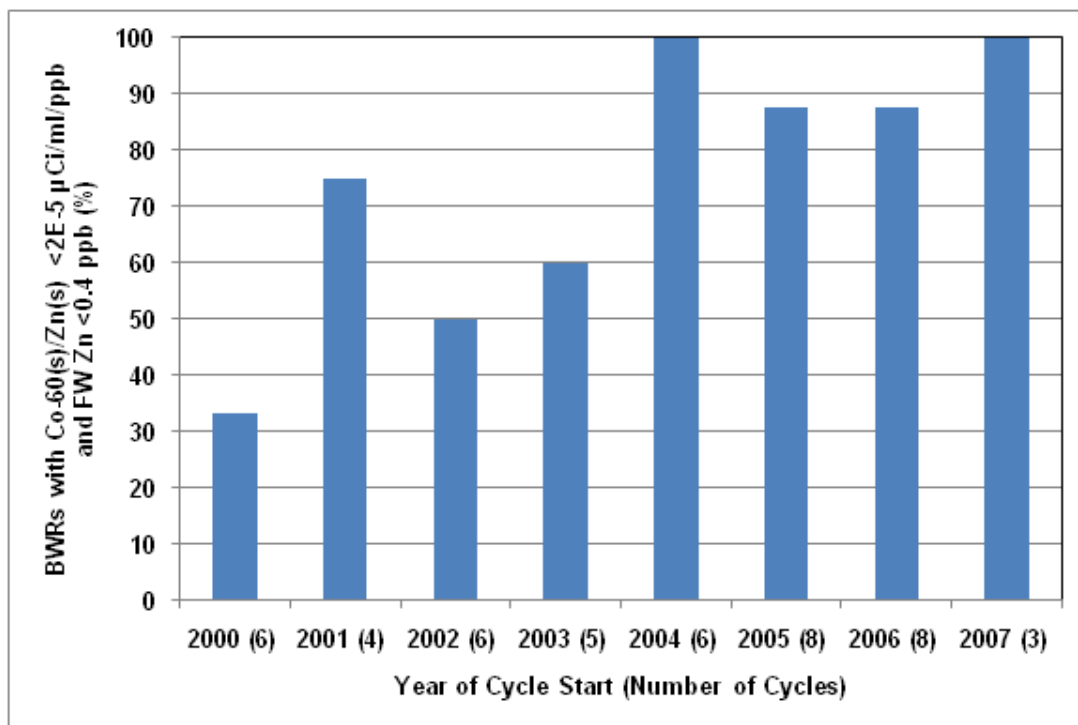


Figure 5-13
BWRs with reactor water Co-60(s)/Zn(s) and feedwater zinc meeting EPRI goals (all cycles, 2000 – 2007)

First Cycle after NMCA

The basis for the BWRVIP-190 reactor water Co-60(s)/Zn(s) goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$ is the dose rate experience at BWRs that initiated HWC prior to NMCA [2]. When data for all plants during the first cycle of NMCA are included, the correlation weakens, and it is weaker still when one outlier plant at 710 mR/hr is eliminated. As discussed above, plants of the BWR 5 and 6 designs, most of which have forward pumped drains, have higher dose rates than earlier BWR designs. Coincidentally, these plants include some of plants that initiated HWC after NMCA.

Average BRAC dose rates measured after the first cycle after NMCA (initial or reapplication), differentiated by BWR type, are plotted against cycle median reactor water Co-60(s)/Zn(s) in Figure 5-14. There is a good correlation for plants of the BWR 2/3/4 designs, and the correlation remains good ($R^2 = 0.7$) even when the outlier plant is removed from the data set. There is a weak correlation for the BWR 5/6 plants when the high BRAC point of 475 mR/hr is eliminated. The same plot is shown with a linear scale in Figure 5-15; this plot is similar to Figure 3-16 of BWRVIP-190 [2]. It is even more apparent in Figure 5-15 that the BRAC dose rates of the BWR 5/6 plants do not follow the same trend as those of the earlier BWR designs.

The data indicate that all BWR 2/3/4 design plants with a cycle median Co-60(s)/Zn(s) less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$ experienced BRAC dose rates below 150 mR/hr in the first cycle after NMCA, and BRAC dose rates at most of these plants were less than 100 mR/hr.

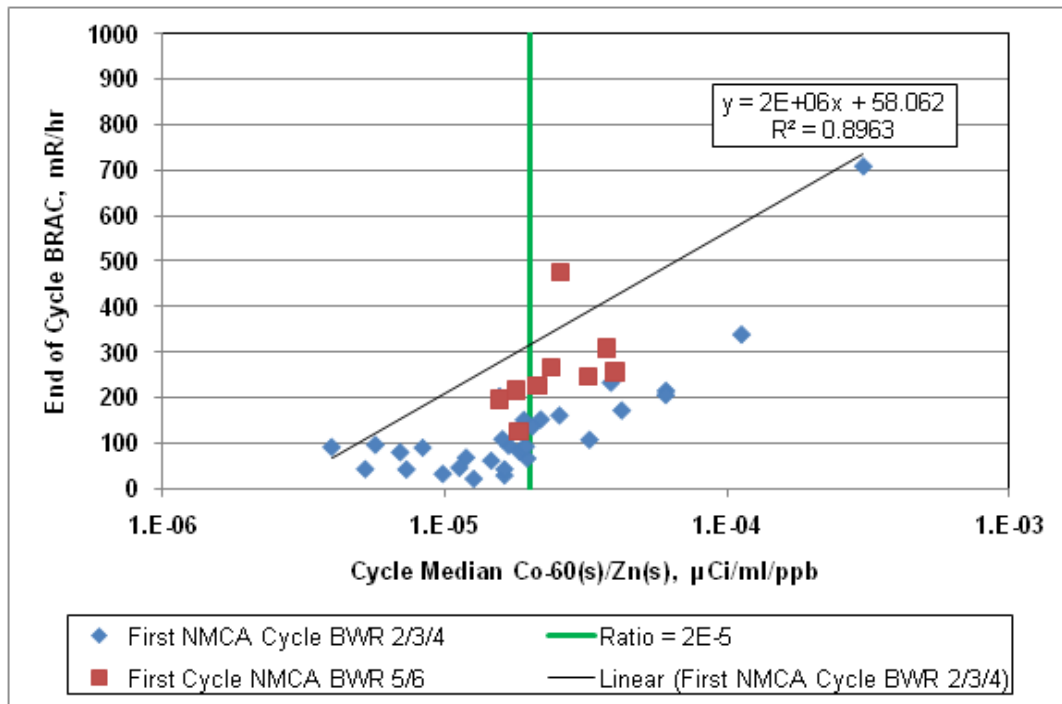


Figure 5-14
BRAC vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (first cycle after initial application or reapplication)

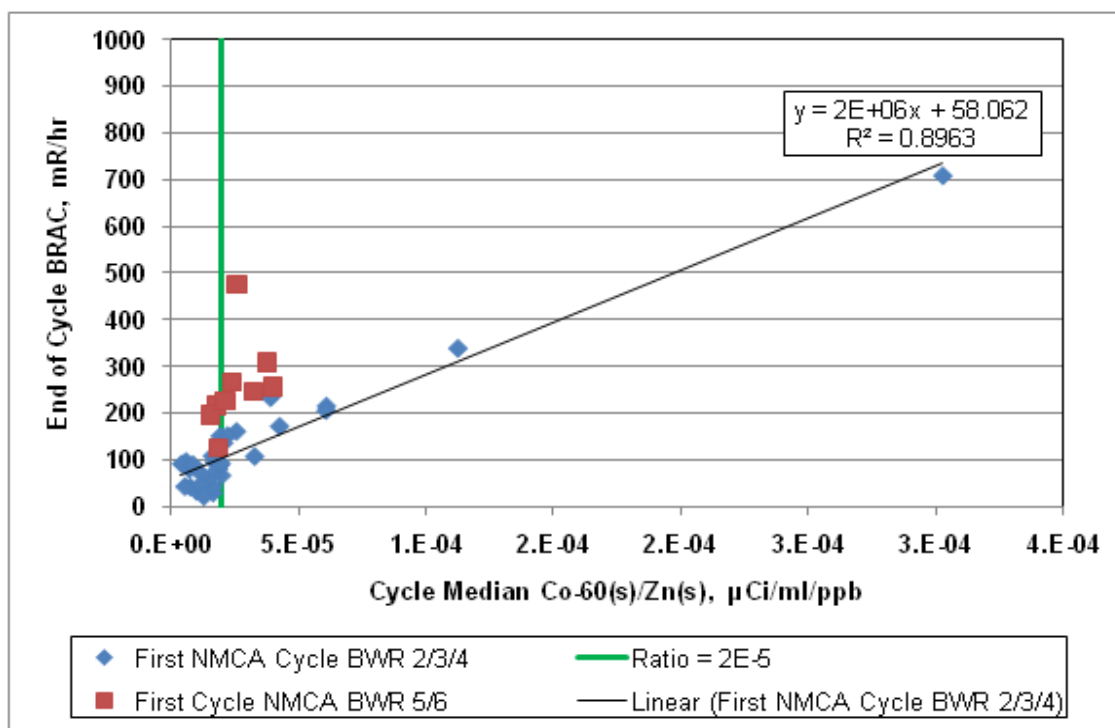


Figure 5-15
BRAC vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (first cycle after initial application or reapplication) – linear scale

The BRAC dose rate change at each BWR during the first cycle after initial NMCA or reapplication is shown in Figure 5-16. Six of eight plants of the BWR 5/6 design experienced dose rate increases while only eight of thirty-one plants of the BWR 2/3/4 design experienced increased average BRAC dose rates (of the eight, four had increases of less than 20 mR/hr). Nineteen of the twenty-five plants that experienced decreased BRAC dose rates in the first cycle after NMCA had a cycle median reactor water Co-60(s)/Zn(s) less than $2E-5$ μCi/ml/ppb. The data indicate that plants of the BWR 2/3/4 design are likely to experience reduced dose rates in the first post-NMCA cycle if they meet the EPRI goal for the Co-60(s)/Zn(s) ratio during the cycle. The data for plants of the BWR 5/6 design are inconclusive.

Second Cycle after NMCA

BRAC results for twenty-seven BWRs, differentiated by BWR type, during the second cycle after NMCA (initial or reapplication) are plotted against cycle median reactor water Co-60(s)/Zn(s) in Figure 5-17. The results are similar to those in Figure 5-14, and indicate a good correlation between BRAC dose rates for plants of the BWR 2/3/4 designs and Co-60(s)/Zn(s) and no correlation for plants of the BWR 5/6 designs. The data indicate an upward trend in BRAC dose rates; however, almost all of the plants of the BWR 2/3/4 designs reported BRAC dose rates less than 200 mR/hr when the reactor water Co-60(s) to Zn(s) ratio was maintained less than $2E-5$ μCi/ml/ppb.

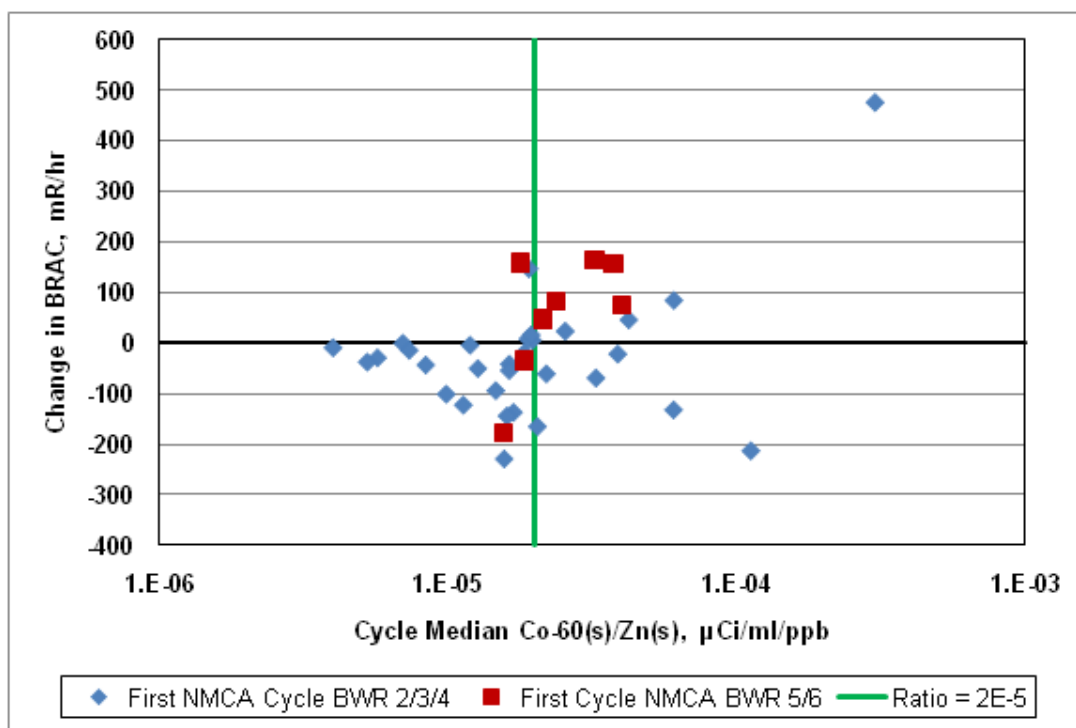


Figure 5-16
Change in BRAC dose rates vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (first cycle after initial application or reapplication)

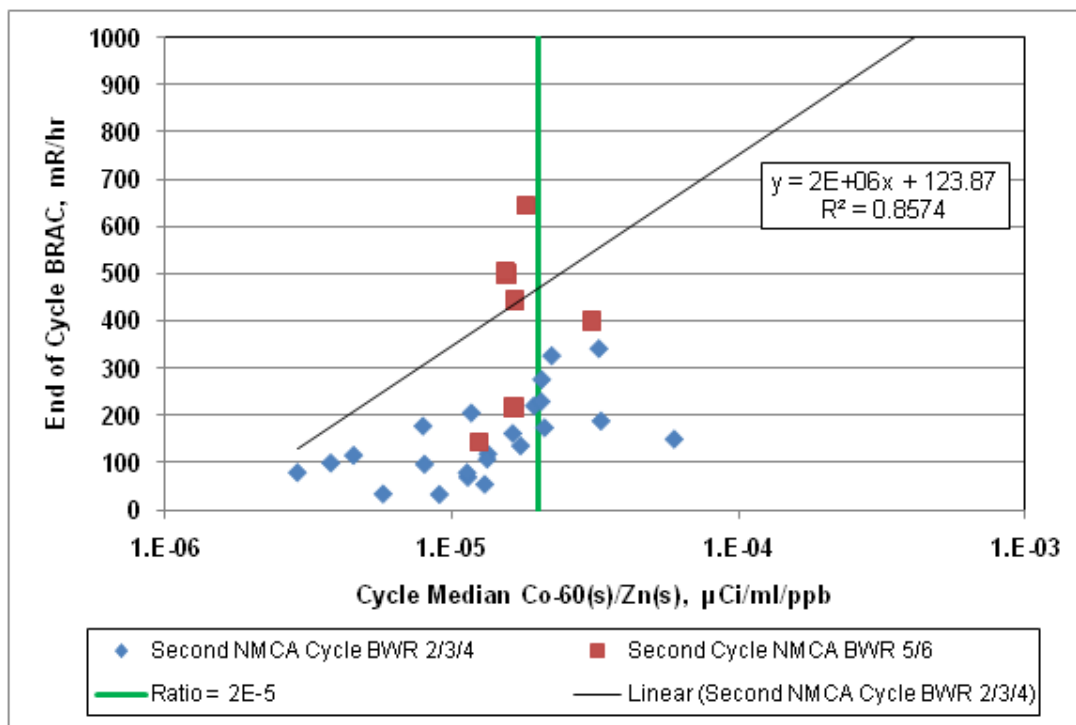


Figure 5-17
BRAC vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (second cycle after initial application or reapplication)

The BRAC dose rate change at each BWR during the second cycle after initial NMCA or reapplication is shown in Figure 5-18. Increased BRAC dose rates were experienced in seven of eight cycles for plants of the BWR 5/6 design, and increases occurred even when the cycle median reactor water Co-60(s) to Zn(s) ratio was maintained less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$. In contrast to the first cycle after NMCA, BRAC dose rates decreased in only six of twenty-three cycles for plants of the BWR 2/3/4 design. The average magnitude of the BRAC decrease was less in the second NMCA cycle, and the average magnitude of the BRAC increase was higher for plants of the BWR 5/6 design. The data indicate that plants were less likely to experience reduced dose rates in the second post-NMCA cycle even when they met the EPRI goal for the Co-60(s)/Zn(s) ratio during the cycle, although plants of BWR 2/3/4 design were more likely to have decreases or small increases in BRAC dose rates.

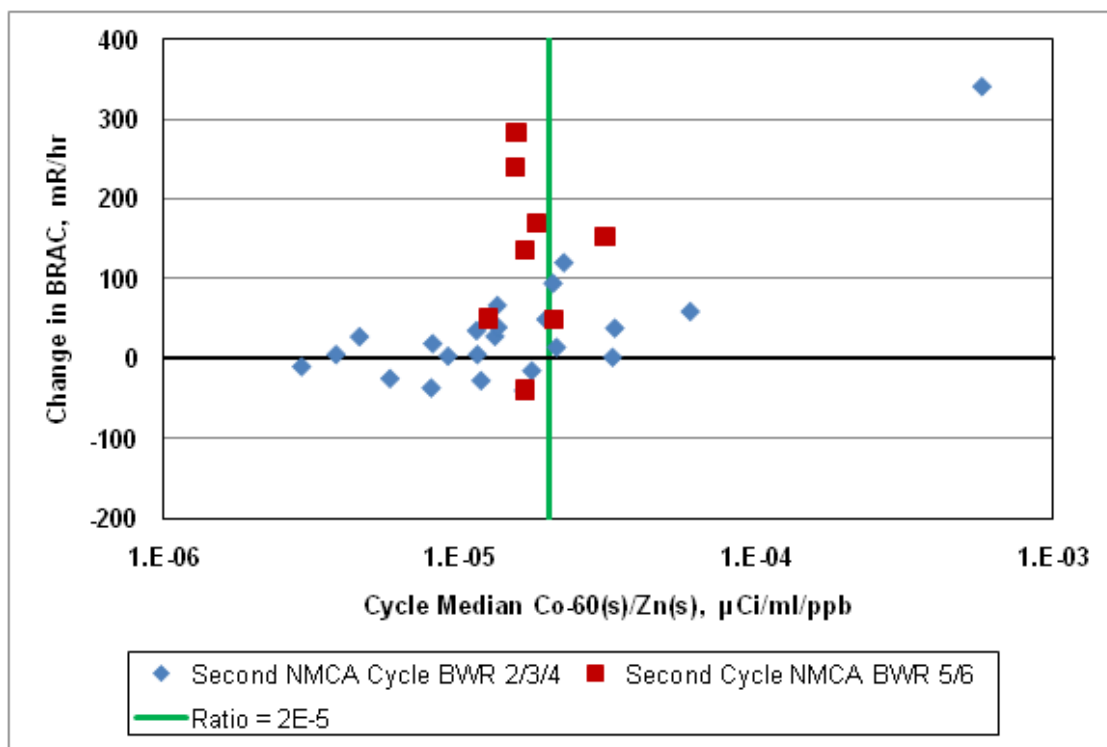


Figure 5-18
Change in BRAC dose rates vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants
(second cycle after initial application or reapplication)

Third Cycle after NMCA

BRAC dose rate results for twenty-four BWRs, differentiated by type, three cycles after initial NMCA are plotted against cycle median reactor water Co-60(s)/Zn(s) in Figure 5-19. For this data set, there is no correlation between BRAC and the ratio for either group of plants. The change in BRAC dose rates for this set of plants is shown in Figure 5-20. As was the case during the second cycle after NMCA, plants were less likely to experience reduced BRAC dose rates in the third cycle after NMCA even when reactor water Co-60(s)/Zn(s) met the EPRI goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$. BWR 2/3/4 plants with reactor water Co-60(s)/Zn(s) less than $1\text{E-}5 \mu\text{Ci/ml/ppb}$ experienced lower dose rates for this data set.

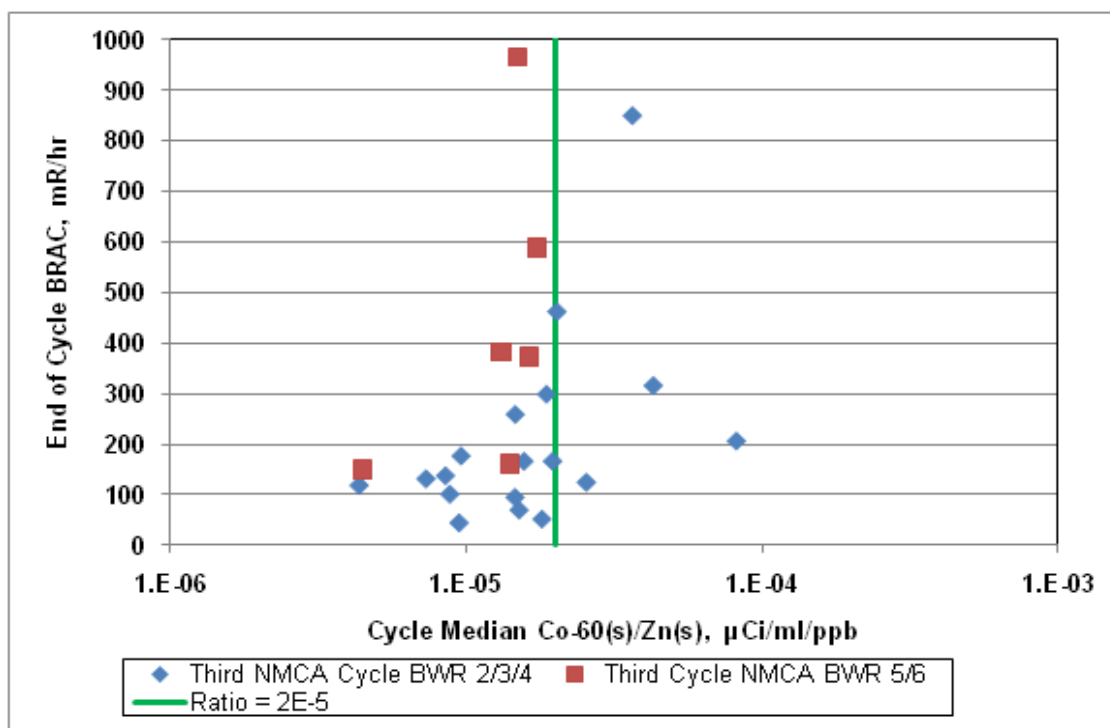


Figure 5-19
BRAC vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (third cycle after initial application)

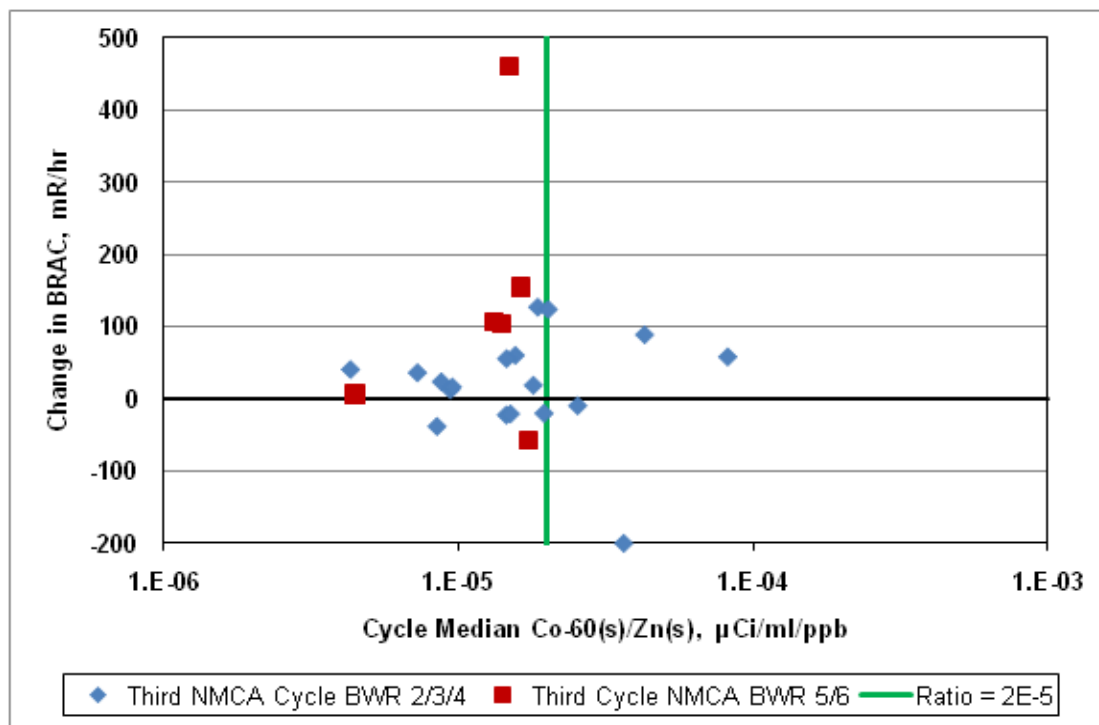


Figure 5-20
Change in BRAC dose rates vs. cycle median reactor water Co-60(s)/Zn(s) for NMCA plants (third cycle after initial application)

Fourth Cycle after NMCA

Data were available for fourteen BWRs four cycles after initial NMCA. Thirteen of these plants maintained a reactor water Co-60(s) to Zn(s) ratio less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$; of these thirteen, ten experienced increased dose rates and three experienced no change or a very small decrease in BRAC dose rates. All reported BRAC values were less than 150 mR/hr.

The current recommendation is to perform NMCA reapplication every 4.5 to 5 years [2], and with the transition of many BWRs to OLNC, it is expected that very few, if any, plants will fall into this category in the future.

OLNC Experience

BRAC data for plants performing OLNC are shown in Table 5-3. Although the number of plants is limited, all plants at which OLNC has been performed have experienced lower or essentially unchanged BRAC dose rates. Leibstadt is the first BWR to implement OLNC as its initial noble metal application, and is the only BWR 5/6 to date that has performed an RFO after OLNC.

Table 5-3
BRAC results for BWRs with OLNC

Plant	NMCA	OLNC	Cycle	Dates	BRAC, mR/hr	Median Rx Co-60(s)/Zn(s), $\mu\text{Ci/ml/ppb}$
Mühleberg	8/00		31	9/03 – 8/04	341	1.49E-5 (1)
Mühleberg		7/05	32	9/04 – 8/05	298	2.24E-5 (1)
Mühleberg		2/06	33	9/05 – 8/06	237	2.71E-5 (1)
Mühleberg		1/07	34	9/06 – 8/07	178	2.23E-5 (1)
Mühleberg		1/08	35	9/07 – 8/08	151	2.18E-5 (1)
Mühleberg		1/09	36	9/08 – 8/09	128	1.96E-5 (1)
Nine Mile Point 1	5/00	12/06	17	4/05 – 3/07	137	1.59E-5
Nine Mile Point 1		11/07 12/08	18	4/07 – 3/09	134	1.82E-5
Peach Bottom 3	10/99	7/07	16	10/05 – 9/07	268	1.72E-5
Peach Bottom 3		2/09	17	10/07 – 9/09	190	1.05E-5 (2)
Leibstadt	n/a		24	9/07 – 8/08	150	2.56E-5 (1)
Leibstadt		11/08	25	9/08 – 8/09	135 (3)	data not complete

Table 5-3 Notes

1. Total Co-60/Zn. Soluble Co-60/Zn ratio would be lower.
2. Through August 2009.
3. Preliminary results.

Recontamination Rates after Chemical Decontamination

Information on recent chemical decontaminations of the reactor recirculation system at twelve BWRs is shown in Table 5-4.

Table 5-4
Recent BWR reactor recirculation system chemical decontaminations

	BRF2	BRF3	COF	CGS	LAS2	NMP1	PER	QUA1	QUA2	RIB	SUS1	SUS2
Chemistry Regime	NMCA	NMCA	HWC-M	NMCA	NMCA	NMCA	NMCA	NMCA	NMCA	HWC-M	HWC-M	HWC-M
Decon Date	Mar-07	Mar-08	May-05	May-07	Feb-05	Apr-05	Feb-09	Mar-05	Mar-04	Jan-08	Mar-04	Mar-03
Process Used	NP-NP-LOMI- NP-LOMI	NP-NP-LOMI- NP-LOMI	CORD-UV	NP-LOMI x3	NP-LOMI- NP-LOMI	NP-LOMI- NP-LOMI	NP-NP-LOMI- NP-LOMI	NP-LOMI- NP-LOMI	NP-LOMI- NP-LOMI		NP-LOMI- NP-LOMI	NP-LOMI- NP-LOMI
Curies Removed		64		~70	61 (Recirc + RWCU)		75.1	89	51		~80	118
DF		17.5	~50 (Recirc A and B avg)	4.5	6 (Recirc), 27 (RWCU)	49 @ BRAC points; 28 overall	10.9 (contact at 25 points)	3.5 - 7.6	7.1		38 (avg @ BRAC points)	
Pre-decon BRAC (mR/hr)	168	325	861	588	444	850	733	462	325	648	285	390
Post-decon BRAC (mR/hr)	34	25	32	87	56	16	82	93	93	71	8.5	12

BRAC recontamination after one cycle at the ten plants that have had a refueling outage is plotted against the cycle median reactor water Co-60(s) to Zn(s) ratio in Figure 5-21. With the exception of one outlier, a general upward trend with increasing soluble Co-60/soluble Zn ratio is evident. Three plants experienced decreased dose rates in the first cycle after chemical decontamination.

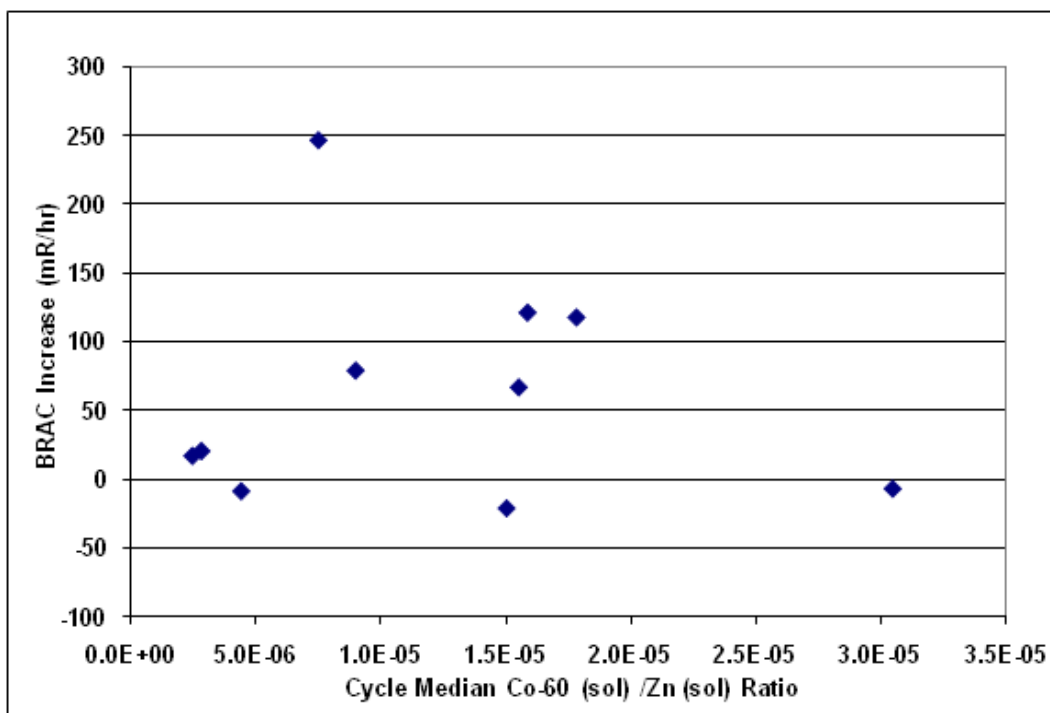


Figure 5-21
BRAC change during first cycle after recirculation system chemical decontamination

Results for plants with increases only are shown in Figure 5-22. For six of these seven plants, there is a good linear correlation between the increase in BRAC dose rates and the cycle median reactor water soluble Co-60 to soluble zinc ratio. The plants in this data set represent both HWC-M and NMCA+HWC plants, and the cycle median ratio at all the plants met the EPRI goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$. When end of cycle BRAC is plotted against the ratio for this data set, the trend is similar and the correlation is improved, as shown in Figure 5-23.

The BRAC dose rate history for the plants with recent decontaminations is shown in Figure 5-24. There are three distinct groups of plants: those with a high initial recontamination rate ($>100 \text{ mR/cycle}$); those with a low recontamination rate ($<25 \text{ mR/cycle}$); and those with a decrease in BRAC dose rates following chemical decontamination.

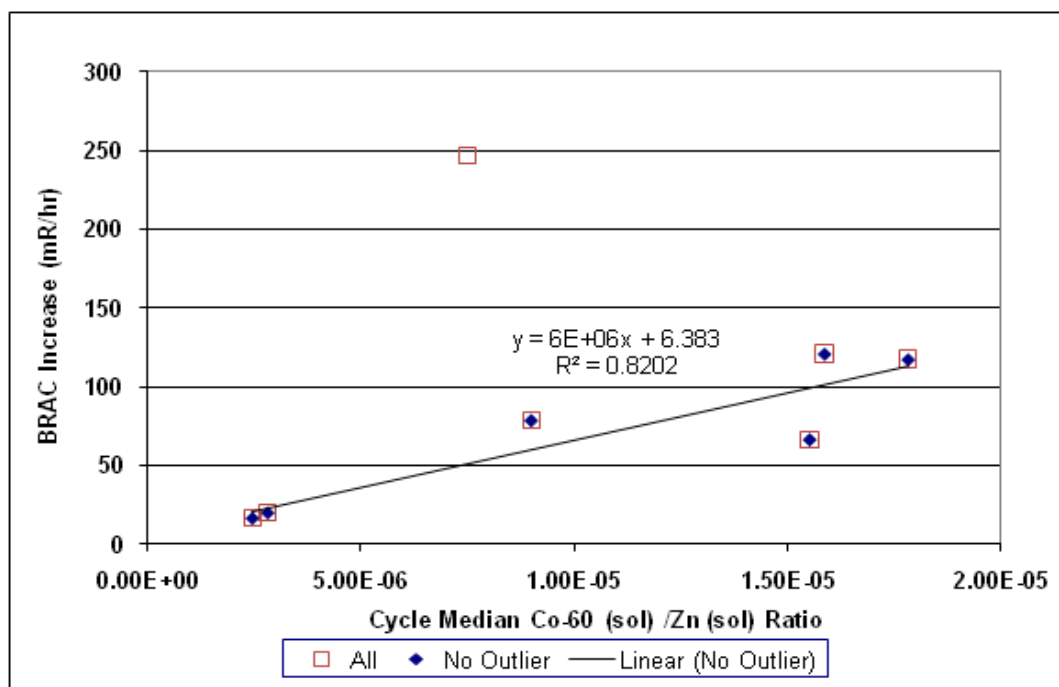


Figure 5-22
BRAC change during first cycle after recirculation system chemical decontamination
(BWRs with increased BRAC only)

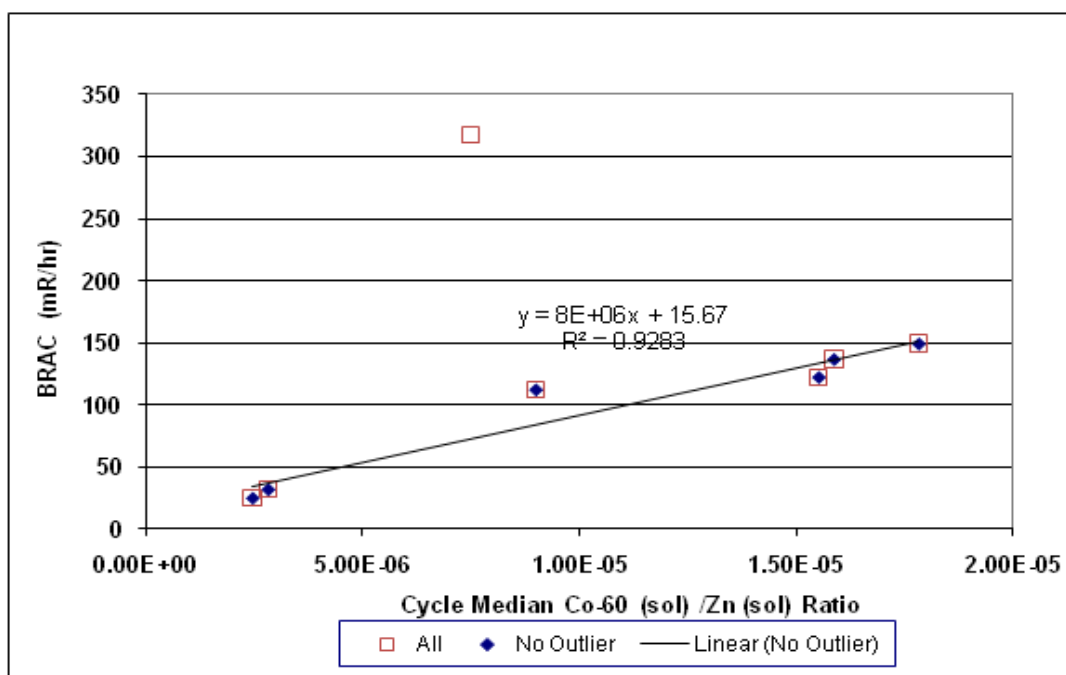


Figure 5-23
BRAC at the end of the first cycle after recirculation system chemical decontamination
(BWRs with increased BRAC only)

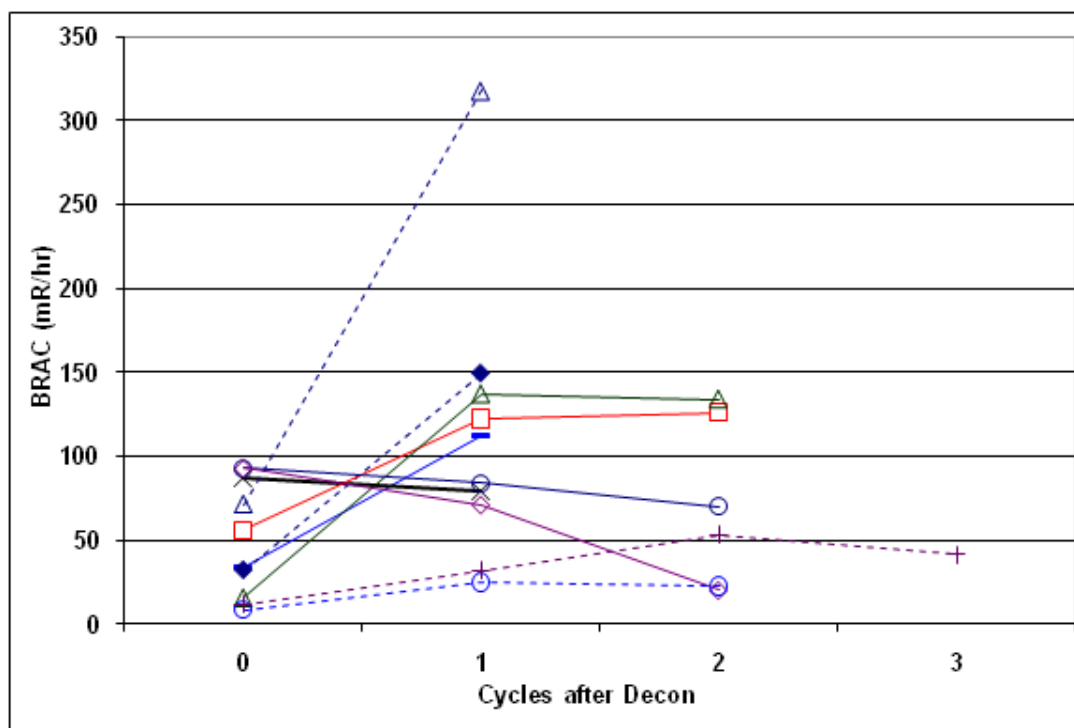


Figure 5-24
BRAC dose rate history for BWRs with recent recirculation system chemical decontaminations

Factors that may contribute to differences in recontamination rates include:

- Low reactor water Co-60(s)/Zn(s) ratio at Susquehanna 1 and 2.
- LTNC at Quad Cities 1 and 2.
- Turbine bucket replacement at Quad Cities 1 and 2 that resulted in lower cobalt source term.
- LaSalle 2 also performed LTNC after the chemical decontamination, but is a higher crud, higher source term plant than the Quad Cities units, and is also a BWR 5 plant.
- River Bend has operated with feedwater iron less than 0.1 ppb for several cycles; however, reactor water soluble Co-60 has been on a decreasing trend since its initial increase after condensate filtration and HWC-M were implemented. Reactor water soluble copper greater than 1 ppb may be a contributing factor to high dose rates at River Bend.

Although initial recontamination was relatively high at LaSalle and Nine Mile Point 1, BRAC dose rates were stable in the second cycle after the chemical decontamination. OLNC was implemented at Nine Mile Point 1 just prior to the end of the first cycle after the chemical decontamination, and an NMCA reapplication was performed at LaSalle 2 at the beginning of the second cycle after the chemical decontamination.

Fleet BRAC Dose Rate Trends

The average and median BRAC dose rates for the BWRs that participate in the BWR Chemistry Monitoring and Assessment project are shown in Figure 5-25. There has been a 32% decrease in average BRAC dose rates between January 2005 and July 2009. Contributors to the decrease include:

- NMCA, including OLNC and LTNC and reapplications
- Chemical decontaminations at plants with high dose rates
- Source term reduction
- Feedwater iron reduction that allows the reactor water Co-60(s)/Zn(s) ratio to be met without exceeding feedwater zinc guidelines.

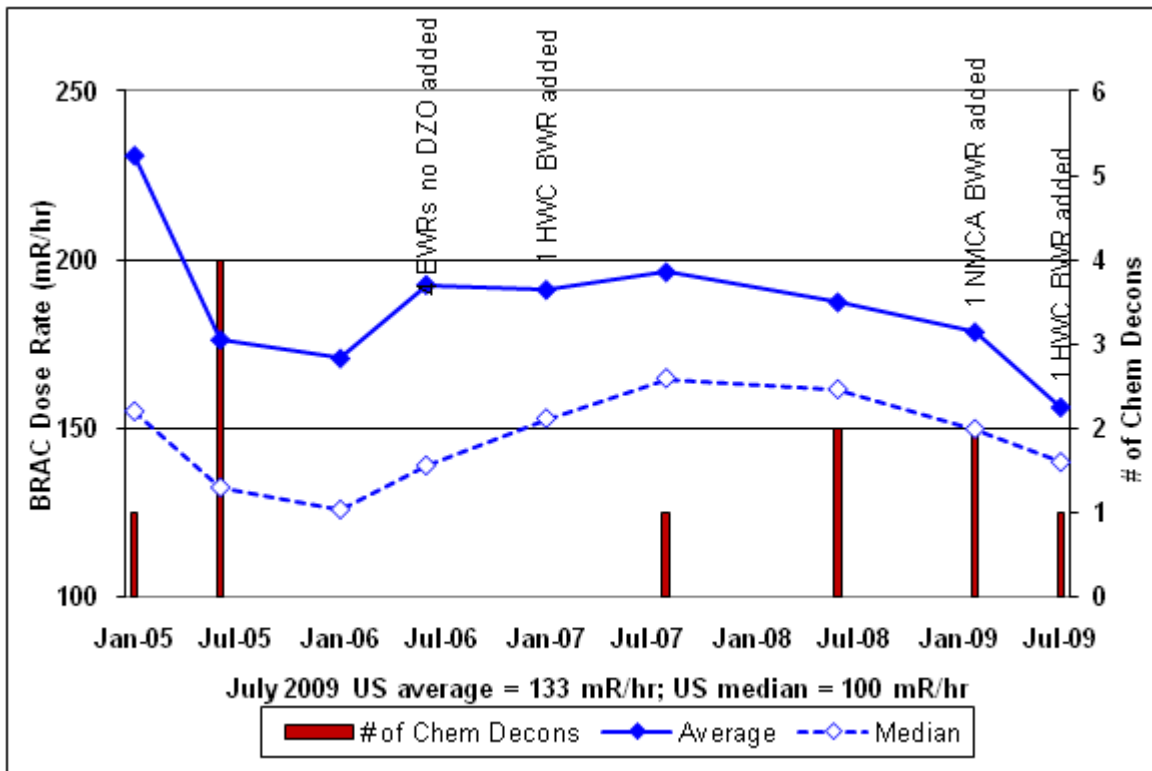


Figure 5-25
BWR fleet average and median BRAC dose rates (2005 – 2009)

Summary

General observations and specific observations for HWC and NMCA plants are summarized below.

General Observations

- There has been a 32% decrease in average BRAC dose rates between January 2005 and July 2009. Contributors to the decrease include: NMCA; chemical decontaminations; and feedwater iron and cobalt source term reduction.
- For six of seven plants that experienced increased BRAC dose rates after recirculation system chemical decontamination, there is a good linear correlation between the increase in BRAC dose rates and the cycle median reactor water soluble Co-60 to soluble zinc ratio. The plants in this data set represent both HWC-M and NMCA+HWC plants, and the cycle median ratio at all the plants met the EPRI goal of $<2\text{E-5 } \mu\text{Ci/ml/ppb}$. When end of cycle BRAC is plotted against the ratio for this data set, the trend is similar and the correlation is improved.

HWC Plants

- There is a weak correlation between BRAC dose rates and Co-60(s)/Zn(s) for Group 1 plants but no correlation is apparent for the Group 2 plants. In addition, the range of BRAC dose rates is narrower for the Group 1 plants compared with the Group 2 plants.
- Ten of thirteen Group 1 plant cycles and thirteen of sixteen Group 2 plant cycles met the Co-60(s)/Zn(s) goal of $<2\text{E-5 } \mu\text{Ci/ml/ppb}$ with a cycle median feedwater zinc concentration less than or near 0.4 ppb.
- For the twenty-five cycles at HWC plants beginning in 2001 through 2005, 32% of plants that met the EPRI reactor water Co-60(s)/Zn(s) goal exceeded the feedwater zinc goal of 0.4 ppb. For the eight plant cycles beginning in 2006 through 2008, all BWRs met both the Co-60(s)/Zn(s) goal and the feedwater zinc goal.

NMCA Plants

All Cycles

- All BWRs with cycle median Co-60(s) less than the EPRI good practice value of $5\text{E-5 } \mu\text{Ci/ml}$ experienced BRAC dose rates less than 200 mR/hr. Plants with lower soluble Co-60 activity can more readily meet the goal of $<2\text{E-5 } \mu\text{Ci/ml/ppb}$ for reactor water Co-60(s)/Zn(s) without exceeding the feedwater zinc goal of less than 0.4 ppb.
- Average BRAC dose rates were less than 200 mR/hr for all cycles when Co-60(s)/Zn(s) was less than $1\text{E-5 } \mu\text{Ci/ml/ppb}$, and all BRAC values less than 100 mR/hr occurred when Co-60(s)/Zn(s) was less than the goal of $2\text{E-5 } \mu\text{Ci/ml/ppb}$.

- For cycles beginning in 2004 - 2007, about 92% of BWR cycles met both the EPRI goals for reactor water Co-60(s)/Zn(s) and feedwater zinc compared to about 52% for cycles beginning in 2000 – 2003.

First Cycle after NMCA

- All BWR 2/3/4 design plants with a cycle median Co-60(s)/Zn(s) less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$ experienced BRAC dose rates below 150 mR/hr in the first cycle after NMCA, and BRAC dose rates at most of these plants were less than 100 mR/hr. There is a good correlation between BRAC dose rates and the Co-60(s) to Zn(s) ratio. There is no correlation between BRAC dose rates and Co-60(s)/Zn(s) for BWR 5/6 plants, and dose rates at these plants are significantly higher than those for BWR 2/3/4 plants.
- BWR 2/3/4 plants are likely to experience reduced dose rates in the first post-NMCA cycle if they meet the EPRI goal for the Co-60(s)/Zn(s) ratio during the cycle. Results for plants of the BWR 5/6 design are inconclusive.

Second and Third Cycles after NMCA

- During the second cycle after NMCA, the data indicate a good correlation between BRAC dose rates for plants of the BWR 2/3/4 designs and Co-60(s)/Zn(s) and no correlation for plants of the BWR 5/6 designs. The data indicate an upward trend in BRAC dose rates; however, almost all of the plants of the BWR 2/3/4 designs reported BRAC dose rates less than 200 mR/hr when the reactor water Co-60(s) to Zn(s) ratio was maintained less than $2\text{E-}5 \mu\text{Ci/ml/ppb}$. Plants were less likely to experience reduced dose rates in the second post-NMCA cycle even when they met the EPRI goal for the Co-60(s)/Zn(s) ratio during the cycle. Plants of BWR 2/3/4 design were more likely to have decreases or small increases in BRAC dose rates.
- During the third cycle after NMCA, there was no correlation between BRAC and the Co-60(s) to Zn(s) ratio. As was the case during the second cycle after NMCA, plants were less likely to experience reduced BRAC dose rates in the third cycle after NMCA even when reactor water Co-60(s)/Zn(s) met the EPRI goal of $<2\text{E-}5 \mu\text{Ci/ml/ppb}$. BWR 2/3/4 plants with reactor water Co-60(s)/Zn(s) less than $1\text{E-}5 \mu\text{Ci/ml/ppb}$ experienced lower dose rates.

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6

PLANT CHEMISTRY IMPACT OF NOBLE METAL APPLICATION

Noble metal chemical application (NMCA) was developed to achieve the BWR ECP specification for mitigation of IGSCC [1] while avoiding the high operating dose rates and high hydrogen gas usage associated with Moderate Hydrogen Water Chemistry. NMCA processes are described in Chapter 2. This chapter updates operating experience at plants that have implemented NMCA and/or OLNC. As of September 2009, thirty-one of the forty-six BWRs that participate in the EPRI BWR Chemistry Monitoring Database have applied noble metals, and six are planning to apply noble metals in the next few years.

Many NMCA/OLNC plants are benefiting from improved IGSCC mitigation while operating with dose reduction benefits and hydrogen cost savings. However, the post-NMCA impact on shutdown dose rates has differed among the plants. Some plants have seen decreases, or no significant change, in shutdown dose rates following NMCA while others have seen increases. Dose rates are discussed in detail in Chapter 5. All plants have observed chemistry transient effects following NMCA. These and other NMCA issues are addressed in BWRVIP-190 [1].

Individual plant responses to NMCA were detailed in earlier reports [2, 3]. BWRVIP-159 [4] provides a summary and description of plant chemistry responses during the operating period following NMCA. RWCU effects after NMCA are included in Chapter 11.

Plants with feedwater sample lines that were contaminated during NMCA continue to experience sampling anomalies such as non-representative dissolved oxygen levels as well as elevated conductivity due to soluble feedwater iron. For example, FitzPatrick is presently in its third cycle following a reapplication in 2004 and continues to experience these anomalies [5]. Reactor water dissolved oxygen concentrations are typically reported as less than detectable at NMCA plants when hydrogen is injected such that the reactor coolant hydrogen:oxidants molar ratio is 2 or greater. This is due to hydrogen and oxygen recombination in the sample line.

Noble Metal Loading

NMCA initial coupon loadings are shown in Table 6-1 and Figure 6-1. The target loading for the first application is approximately $1 \mu\text{g}/\text{cm}^2$. The loading achieved in the application is normally based on the measured NMCA coupon loading results. The amount deposited in the primary system during the application may also be estimated by a mass balance. The mass balance calculates the combined mass of platinum and rhodium deposited on surfaces, primarily the fuel.

Table 6-1
Noble metal application initial coupon loading

Plant	First Application		Reapplication	
	Date	Noble Metal Loading ($\mu\text{g}/\text{cm}^2$)	Date	Noble Metal Loading ($\mu\text{g}/\text{cm}^2$)
Browns Ferry 1	Nov-07	1.59	none	
Browns Ferry 2	Mar-01	0.95	Apr-09	0.97
Browns Ferry 3	Apr-00	1.03	none	
Clinton	Apr-02	0.75	Jan-08	1.66
Columbia	May-01	0.51	May-07	0.89
Cooper	Mar-00	0.65	Jan-05	0.79
Dresden 2	Oct-99	0.80	Oct-03	0.21
Dresden 3	Sep-00	0.30	Nov-06	1.15
Duane Arnold	Oct-96	0.22	Oct-99 Mar-05	0.80 1.45
FitzPatrick	Nov-99	1.18	Sep-04	0.35
Hatch 1	Mar-99	0.70	Feb-06	0.61
Hatch 2	Mar-00	1.30	Feb-07	0.41
Hope Creek	Apr-06	1.58	none	
Laguna Verde 1	Sep-05	1.42	none	
Laguna Verde 2	Apr-06	2.03	none	
LaSalle 1	Oct-99	0.70	Feb-06	0.28
LaSalle 2	Nov-00	1.00	Feb-05 (1) Feb-07	2.33 0.72
Leibstadt	Nov-08 (2)	OLNC (3)		
Limerick 1	Mar-00	1.16	Mar-08	0.97
Limerick 2	Apr-01	1.12	Mar-07	0.54
Mühleberg	Aug-00	0.87	Jul-05 (2)	OLNC (3)
Nine Mile Point 1	May-00	2.10	Dec-06 (2)	OLNC (3)
Nine Mile Point 2	Sep-00	1.00	Dec-07 (2)	OLNC (3)
Oyster Creek	Oct-02	0.32	Nov-08	1.08
Peach Bottom 2	Oct-98	2.80	Sep-06	1.20
Peach Bottom 3	Oct-99	0.66	Jul-07 (2)	OLNC (3)
Perry	Feb-01	0.90	Apr-07 (4) Nov-08	4.10 OLNC (3)
Pilgrim	Apr-07	1.20 (plant) 0.39 (GE)	none	
Quad Cities 1	Apr-99	0.60	Mar-05 (1) May-07	1.58 1.73
Quad Cities 2	Jan-00	2.33	Mar-04 (1) Mar-06	1.89 0.47
Vermont Yankee	Apr-01	1.24	May-07	0.63

Table 6-1 Notes

LTNC after recirculation system chemical decontamination.

First OLNC application.

<0.1 $\mu\text{g}/\text{cm}^2$ fuel surface area.

LTNC after RWCU system chemical decontamination.

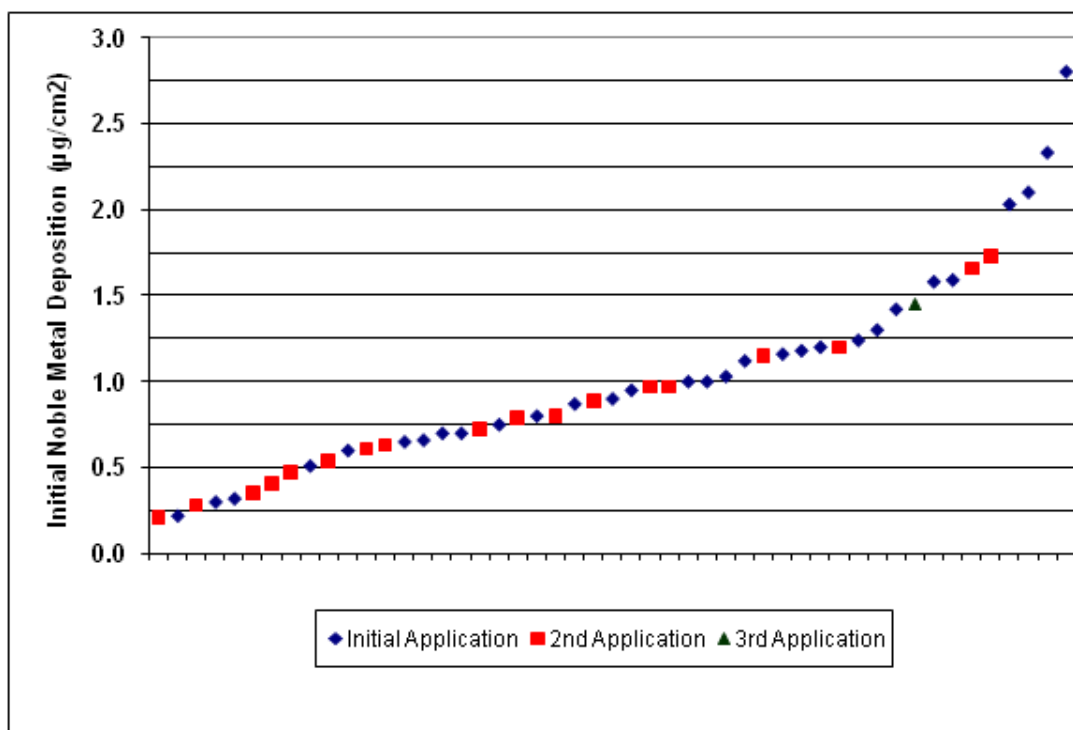


Figure 6-1
Noble metal initial coupon loading

The highest initial NMCA coupon loading was at Peach Bottom 2 during the station's first application in 1998. The lowest initial coupon loading was at Dresden 2 in the reapplication in 2003. The high deposition at Peach Bottom 2 occurred prior to the current fuel deposition limit of $30 \mu\text{g}/\text{cm}^2$. As discussed in the 2005 edition [3], Dresden 2 and FitzPatrick were the first two high crud plants to perform a reapplication. Both plants experienced elevated iron crud in the reactor coolant during the shutdown leading up to the reapplication and during the reapplication which interfered with achieving the desired coupon deposition. Most likely, high crud also resulted in the low deposition at Oyster Creek in its first application in 2003.

A plot of the calculated noble metal deposition on the fuel surfaces versus application date is shown in Figure 6-2. For some applications, the net injection amount, adjusted by the calculated RWCU removal term, is also plotted. The plot shows that plants began implementing the industry recommendation to limit fuel surface deposition to $30 \mu\text{g}/\text{cm}^2$ in 2000 - 2001.

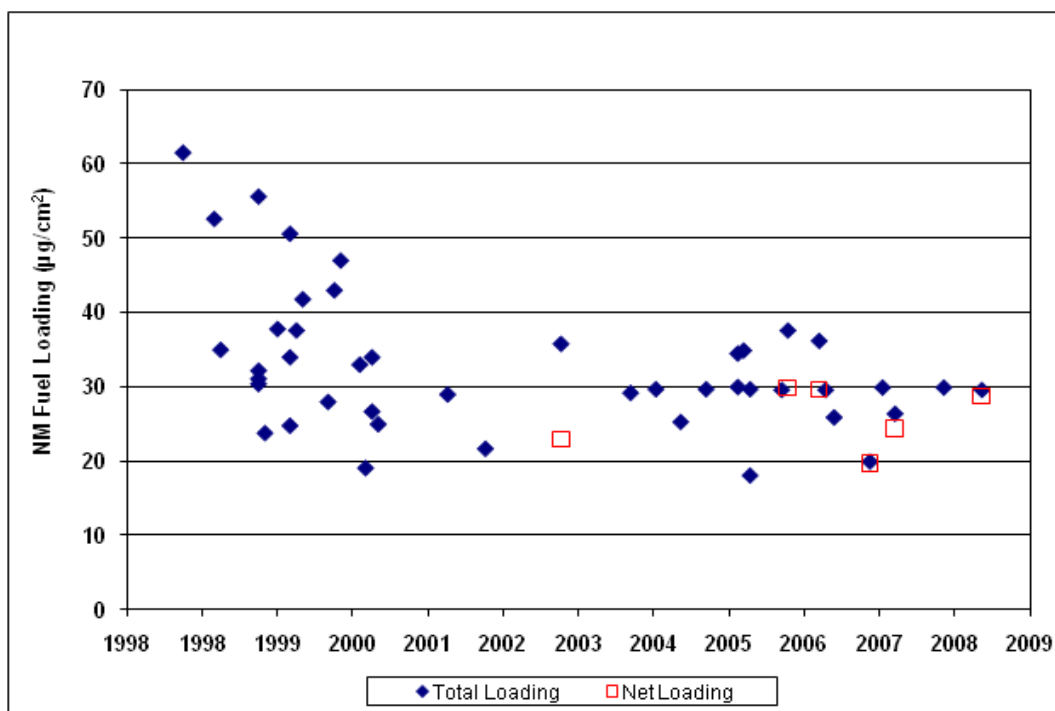


Figure 6-2
Industry NMCA calculated noble metal fuel loading

Over time, the amount of noble metal on the reactor components and recirculation piping will decrease and reapplication will be required. To estimate when reapplication is required, durability monitoring is performed using a Mitigation Monitoring System (MMS). The MMS contains a number of coupons, which are treated during the noble metal application and are exposed to reactor coolant during plant operation. The flow in the MMS is set to approximately match the velocity at the surface of an in-vessel component, such as the shroud at a specified location. The coupons are removed at periodic intervals and analyzed to quantify the amount of noble metal remaining on the coupon surface. By trending the noble metal loading, projections can be made to estimate when reapplication will be required. GEH Services Information Letter (SIL) # 659 [6] provides recommendations on when to reapply NMCA. SIL #659 supersedes reapplication recommendations in BWRVIP-190. For NMCA, SIL # 659 recommends reapplication every 4 years for plants on a 12- or 24-month cycle, and every 4.5 years for plants on an 18-month cycle, or when the measured deposition on durability monitor coupons is $< 0.1 \mu\text{g}/\text{cm}^2$, whichever comes first.

Loadings on removed application coupons with the longest exposure time for individual plants for which data are available are shown in Table 6-2. In some cases, removed coupons show a deposition higher than the initial coupon loading. This may be due to redistribution and/or to variation in initial deposition caused by variation in coupon surface conditions related to the tubing fabrication process and pre-oxidation process. The initial depositions shown in Table 6-2 may differ from the values in Table 6-1 due to variations in the plant and MMS coupon results.

Table 6-2
Noble metal coupon loading ($\mu\text{g}/\text{cm}^2$) – longest in-service removed application coupons

Plant	Initial Coupon Loading	Date of Removal	Exposure Time (months)	Coupon Loading	% of Initial
Browns Ferry 1	1.59	11/08	12	0.84 (1)	53 (1)
Browns Ferry 3	1.03	10/05	52	0.82 (2)	60 (2)
Clinton	1.1 (2)	9/05	36	1.19	> 100
Cooper	0.65	1/04	15	0.65	100
Dresden 2	0.80	2/04	15	2.26	> 100
Dresden 2 (2 nd application)	0.21	6/06	27	0.43	> 100
Dresden 3	0.81 (3)	3/05	34	0.69	86
Duane Arnold	0.22	~11/98	25	0.13	58
FitzPatrick	1.18	10/04	60	0.29	25
FitzPatrick (2 nd application)	0.97	10/08	49	0.58	60
Hatch 2	1.38	4/05	51	1.10	81
Hope Creek	1.58	12/08	28	2.13	> 100
LaSalle 1 (2 nd application)	0.28	2/08	24	0.25	89
LaSalle 2	1.28	11/04	7	1.11	87
LaSalle 2 (2 nd application)	2.33	1/08	35	0.54	23
Limerick 1	1.15	12/05	60	0.45	39
Limerick 2	1.12	3/05	43	0.94	84
Nine Mile Point 1	2.10	3/03	18	1.50	71
Nine Mile Point 2	0.80	5/03	27	0.66	83
Oyster Creek	0.32	4/07	48	0.28	92
Peach Bottom 2	2.80	11/03	56	0.95	68 (4)
Peach Bottom 3	0.60	11/03	45	0.52	87
Quad Cities 1	1.18	2/05	64	0.44	36
Quad Cities 1 (2 nd application)	1.63	11/08	18	1.12	68
Quad Cities 2	2.33	8/05	60	1.72	75
Quad Cities 2 (2 nd application)	0.47	8/08	27	0.33	70
Vermont Yankee	1.24	3/04	31	1.18	95

Table 6-2 Notes

1. Average of 2 coupons.
2. Initial plant coupon deposition (stainless steel coupon).
3. Initial plant coupon deposition.
4. Based on GE coupon of $1.4 \mu\text{g}/\text{cm}^2$.

Noble metal coupon deposition versus exposure time is shown in Figure 6-3 for plants for which data were available. There is a considerable amount of scatter in the data prior to about 40 months of exposure. After 40 months, the data indicate a steep linear drop in the remaining deposit with time, which supports the reapplication frequency recommendation in GEH SIL #659 [6].

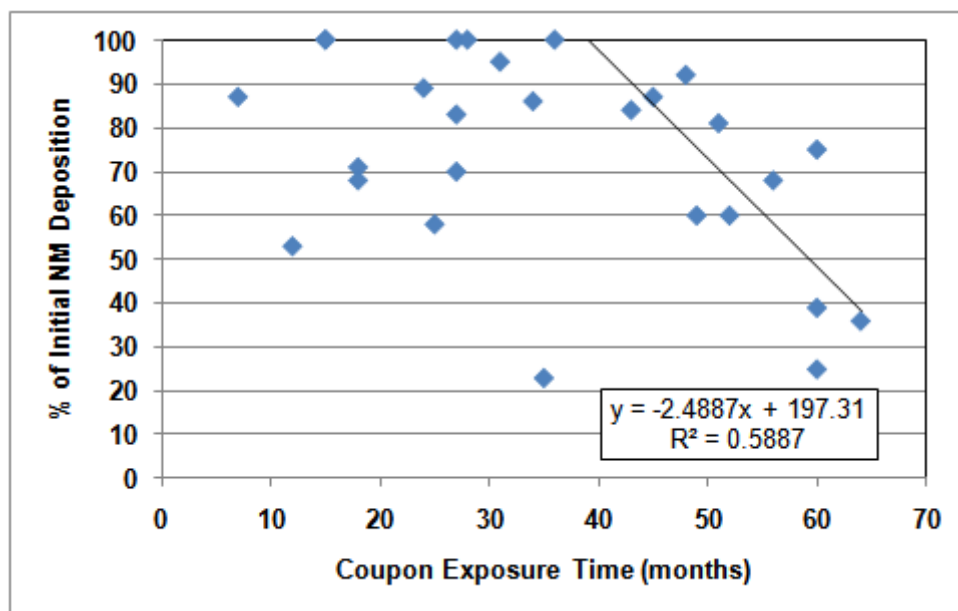


Figure 6-3
Noble metal coupon deposition vs. exposure time

The OLCN process applies significantly lower amounts of noble metal per application than NMCA. Plants performing OLCN have installed coupons in the MMS to monitor the application process. As noted in Appendix C of BWRVIP-190 [1], the highest observed coupon deposition during an OLCN was $0.06 \mu\text{g}/\text{cm}^2$, with a calculated average deposition for all plants performing an OLCN through mid 2008 of $0.03 \mu\text{g}/\text{cm}^2$. SIL # 659 [6] recommends that plants using OLCN should reapply every 11-16 months, with each nominal application input $< 10 \mu\text{g}/\text{cm}^2$, normalized over all fuel rod surface areas.

Recent Application Experience

Initial Applications

Browns Ferry 1 was the most recent plant to complete an initial NMCA. The application was performed mid-cycle, in November 2007, approximately six months after the unit had been restarted following an extended shutdown of 20 years. As shown in Table 6-1, the noble metal loading during the application was $1.59 \mu\text{g}/\text{cm}^2$. The equipment upgrades to support restart resulted in a significant reduction in cobalt source term, including the replacement of the remaining eighty-five control rod blades that contained Stellite™ pins and rollers. The recirculation piping was replaced prior to restart. In the first refuel outage following the noble metal application (November 2008), the BRAC dose rate measurement was about 15 mR/hr. Reactor water soluble Co-60 did not increase significantly following NMCA.

Leibstadt performed an OLNC in November 2008, the first station to perform OLNC as its initial application. The station operated with NWC until September 2008, when HWC operation began. Depleted zinc oxide (DZO) injection was initiated in 1990. The station has ECP electrodes installed in an MMS, a recirculation system flange, and in the reactor sample system. All electrodes responded favorably to the noble metal injection. Other chemistry and plant responses, such as activated corrosion products, reactor coolant conductivity, and main steam line radiation were typical of OLNC experience at other plants. Chemistry data after the OLNC were not available at the time of this report.

NMCA Reapplications

Four plants have performed NMCA reapplications since 2007.

Clinton performed a reapplication in January 2008. The achieved deposition of $1.55 \mu\text{g}/\text{cm}^2$ was more than twice as high as that achieved during the initial NMCA. The station observed a smaller increase in soluble and insoluble Co-60 concentrations following the 2008 reapplication than that observed following the initial application.

Limerick 1 performed a reapplication in March 2008. The station achieved a deposition of $0.97 \mu\text{g}/\text{cm}^2$, which was about 20% lower than the initial application deposition in March 2000. The station observed a larger increase in soluble and insoluble Co-60 concentrations following the 2008 reapplication than that observed following the initial application.

Oyster Creek performed a reapplication in November 2008. The station achieved a deposition of $1.08 \mu\text{g}/\text{cm}^2$, which is more than a factor of three higher than the initial application in October 2002. Lower feedwater iron after implementation of full flow condensate filtration in 2007 likely contributed to the improved deposition in 2008. Co-60 activity increased for approximately nine months after the reapplication, after which levels began to decrease.

Browns Ferry 2 reapplied noble metals in April 2009. The station achieved a deposition of $0.97 \mu\text{g}/\text{cm}^2$, about the same as that of the initial application in March 2001. Feedwater iron has decreased significantly at Browns Ferry 2 since 2004. Prior to 2004, feedwater iron was normally reported between 1 and 2 ppb, decreasing to less than 1 ppb in mid-2004 with concentrations less than 0.2 ppb reported since September 2007. As with the Oyster Creek reapplication, lower feedwater iron may be a contributing factor to the improved deposition observed at Browns Ferry 2. Recent data indicate a larger increase in reactor water soluble Co-60 following the reapplication than was observed after the initial application.

OLNC Applications

Four BWRs have implemented OLNC after NMCA since 2007.

Nine Mile Point 1 has completed three OLNC applications since December 2006. The station has operable ECP probes in the MMS (RWCU inlet sample) and in a reactor recirculation flange. A plot of ECP data is shown in Figure 6-4. The beginning of each OLNC application is indicated by a vertical line in the plot. In the refuel outage prior to the first online injection, the station had performed a chemical decontamination of the reactor recirculation system. The first OLNC

was performed about twenty months into the operating cycle following the chemical decontamination. LTNC was not performed following the decontamination. Thus, for the twenty-month period between the chemical decontamination and the first OLNC, the recirculation piping was not mitigated. Measured ECP from the reactor recirculation system ranged between -100 to 0 mV (SHE).

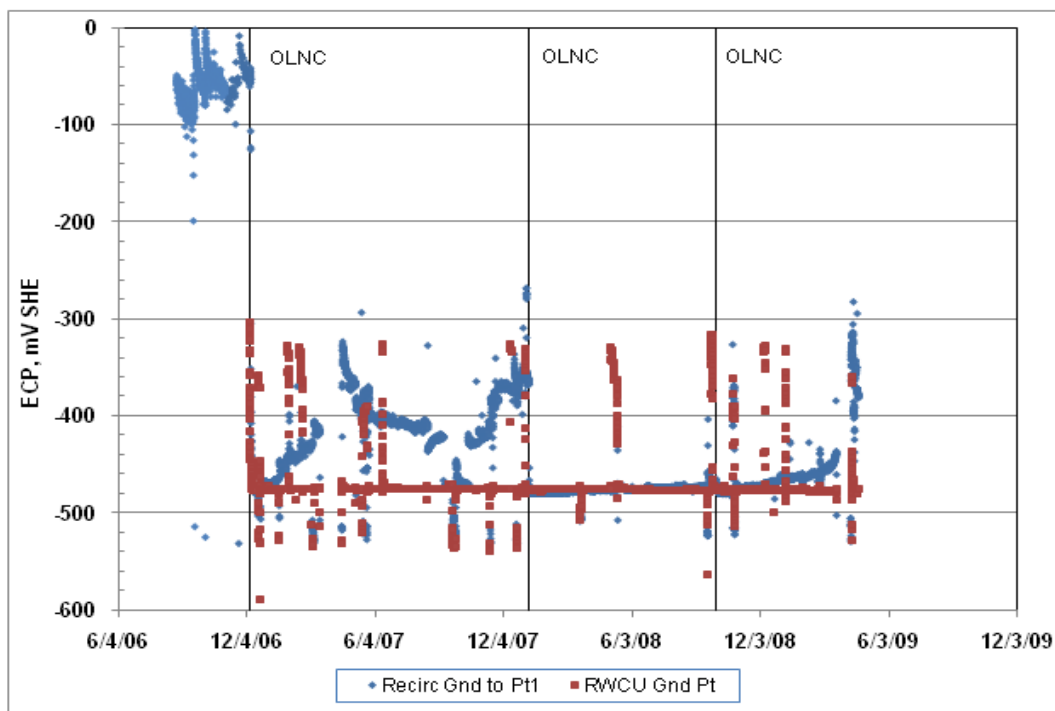


Figure 6-4
Nine Mile Point 1 MMS (RWCU sample) and recirculation flange ECP trends

As shown in the plot, both ECP measurements responded favorably to the first OLNC injection (prior to the OLNC, the MMS manifold was replaced so that a response could be seen when noble metal from the OLNC deposited on the surface). Prior to the March 2007 refuel outage, the recirculation flange ECP readings began increasing. At the start of the next operating cycle, the flange ECP reading was initially about -320 mV (SHE) but later decreased to below -400 mV (SHE). By the time of the second OLNC, the flange ECP reading again was near -300 mV (SHE). The second OLNC achieved a similar response in the flange ECP as the first OLNC with a quick drop in ECP to near -480 mV (SHE). There was no change in the MMS ECP as a result of the OLNC. By the time of the third OLNC, the flange and MMS ECP values were nearly identical, at about -480 mV (SHE). The third OLNC produced virtually no change in either ECP value. The recirculation flange ECP began to increase towards the end of the operating cycle. The next OLNC at Unit 1 is scheduled for late 2009.

Co-60 data are plotted in Figure 6-5. The plot shows a cyclical data trend in both the soluble and insoluble fractions. The OLNC produced a change in both fractions; although the magnitude of the change was smaller than what has been seen at some stations following NMCA, the peak concentrations increased following each application. BRAC dose rates have been stable at Unit 1 since the first OLNC and are significantly lower than the dose rates prior to the 2005 reactor recirculation system chemical decontamination.

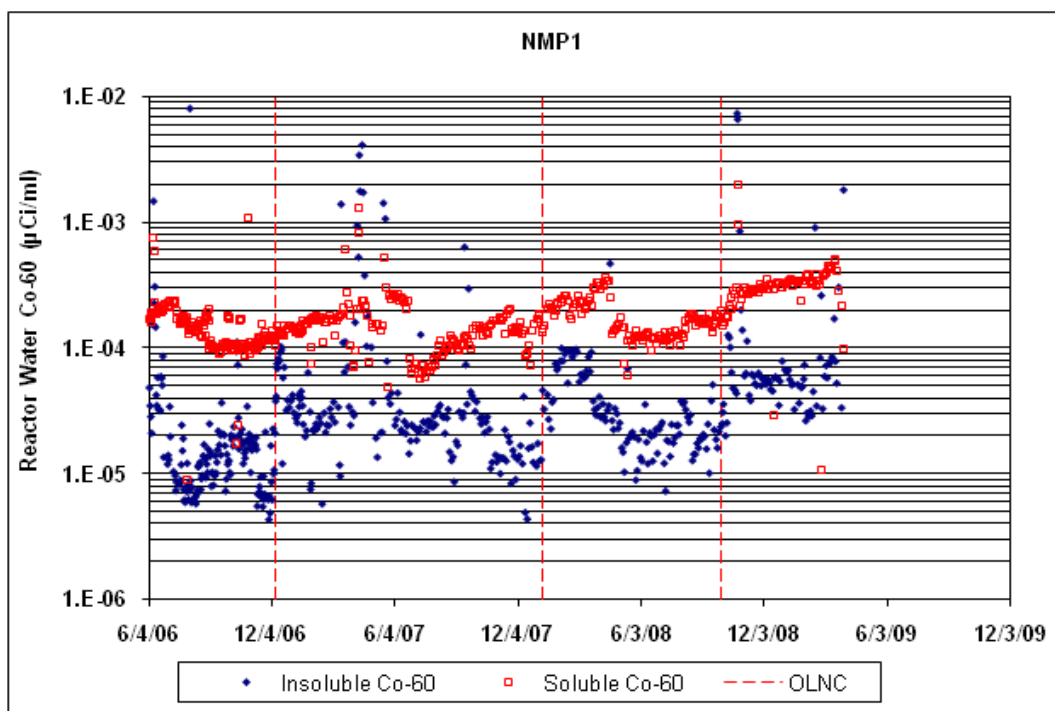


Figure 6-5
Nine Mile Point 1 reactor coolant Co-60 trends

Nine Mile Point 2 has completed two OLNC injections; the first occurring in December 2007, and the second in December 2008. As shown in Figure 6-6, the station observed a significant increase in both the soluble and insoluble Co-60 fractions following the first OLNC, comparable to NMCA. Early indications are that the changes in the Co-60 fractions were not as significant after the second OLNC, peaking at $2.9\text{E-}4$ $\mu\text{Ci/ml}$.

Peach Bottom 3 has performed three OLNC injections; the first in July 2007, the second in April 2008, and the third in February 2009. The station observed a slight increase in the soluble Co-60 fraction following the first OLNC and a larger increase in the insoluble fraction, as shown in Figure 6-7. Prior to the second OLNC, soluble Co-60 was on a decreasing trend. As a result, the change in the soluble fraction following the second OLNC was larger than the first OLNC, although the soluble fraction reached a steady state peak value of about $1.8\text{E-}4$ $\mu\text{Ci/ml}$ after both applications. The first OLNC was performed about three months before a refuel outage (RFO16).

Perry performed OLNC in November 2008, about three months prior to a refueling outage. As shown in Figure 6-8, the increase in both soluble and insoluble Co-60 in the initial period following OLNC was less than that following NMCA. The subsequent increases are related to the refueling outage and limited steady state power data after the RFO are available. BRAC dose rates decreased from 965 mR/hr to 733 mR/hr in the RFO three months after OLNC when a recirculation system chemical decontamination was performed.

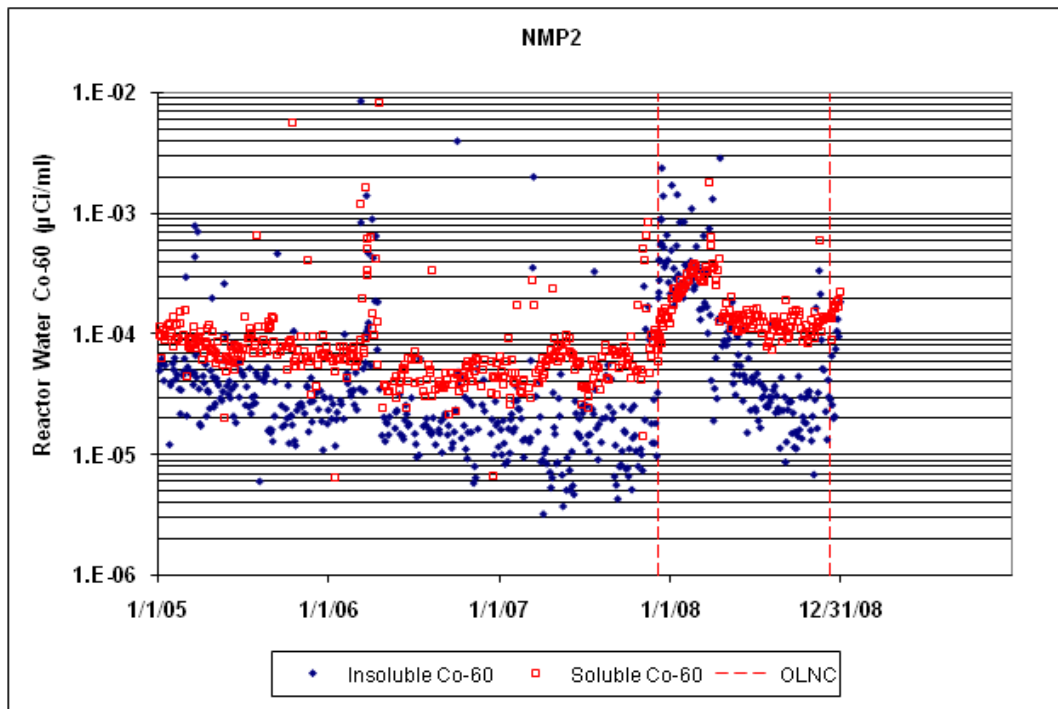


Figure 6-6
Nine Mile Point 2 reactor coolant Co-60 trends

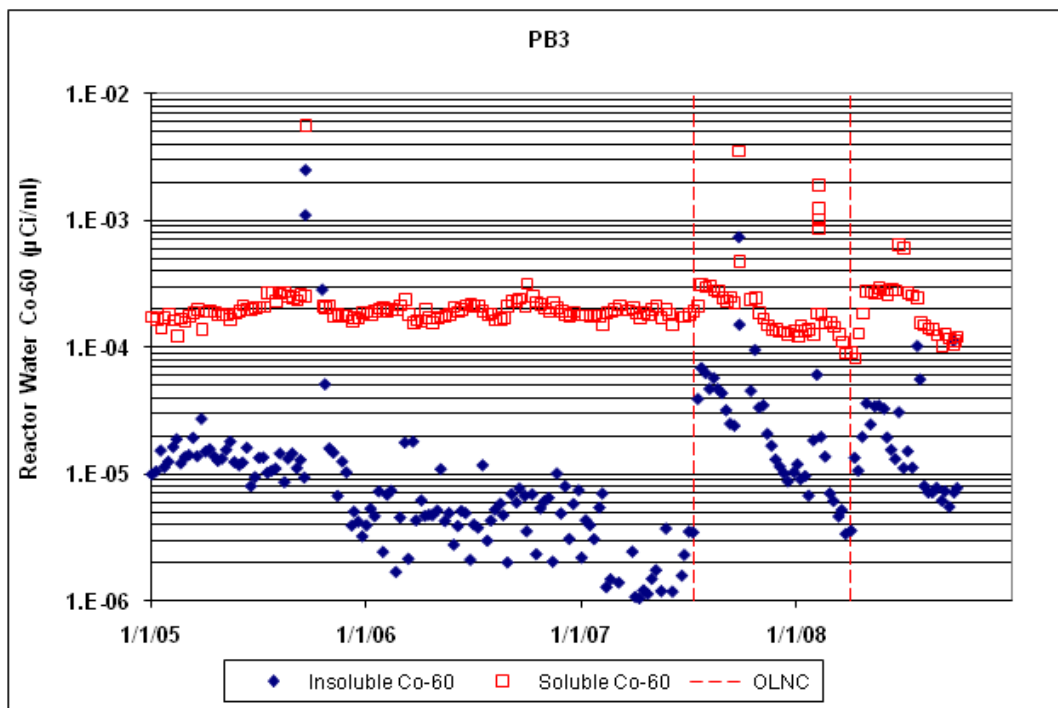


Figure 6-7
Peach Bottom 3 reactor coolant Co-60 trends

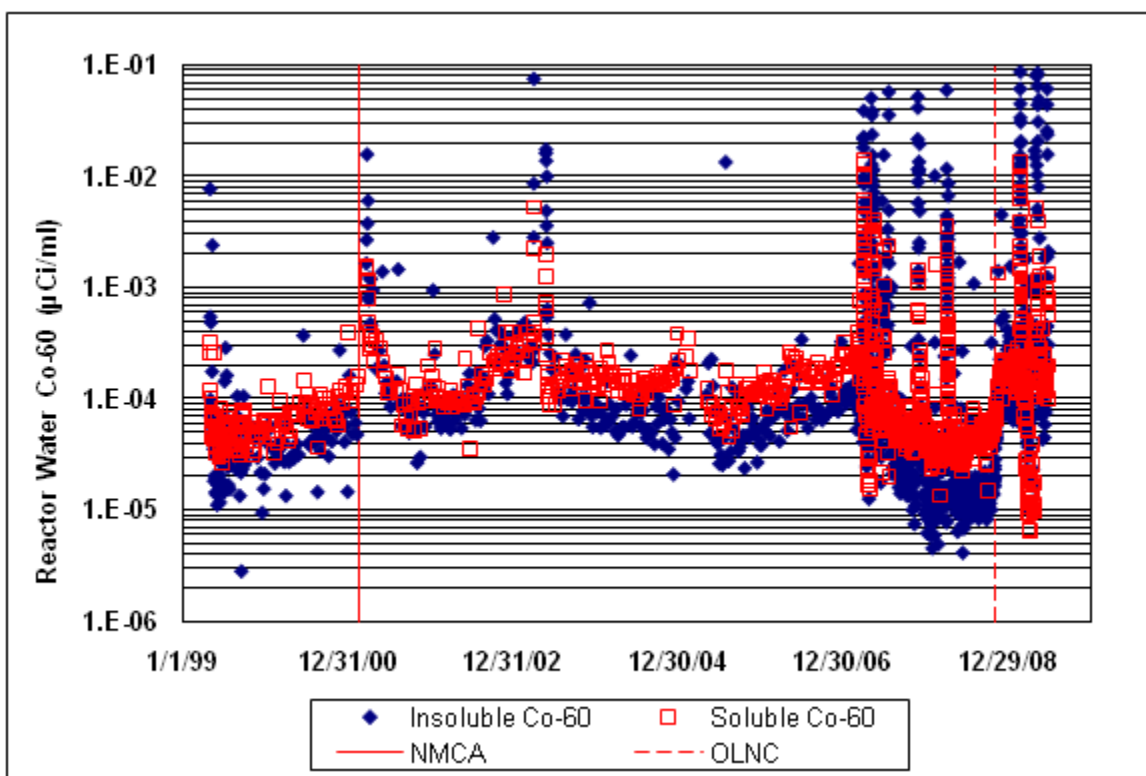


Figure 6-8
Perry reactor coolant Co-60 trends

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7

PLANT CHEMISTRY MONITORING PRACTICES AND COMPLIANCE WITH EPRI BWR WATER CHEMISTRY GUIDELINES – 2008 REVISION

Introduction

Chemistry monitoring plays an important role in evaluating plant chemistry performance with respect to the following goals:

- Minimizing intergranular stress corrosion cracking (IGSCC) to ensure long term asset protection
- Providing assurance of fuel reliability through reduction of corrosion products transport to the fuel
- Minimizing shutdown radiation dose rates
- Controlling FAC (Flow-Accelerated Corrosion)

The 2008 revision of the EPRI BWR Water Chemistry Guidelines [1] recognizes the importance of these goals through recommendations for chemistry optimization and chemistry action levels and the mandatory requirement for the development of a Strategic Water Chemistry Plan. This section discusses chemistry monitoring practices, focusing on current and planned compliance with the recommendations in the EPRI BWR Water Chemistry Guidelines – 2008 Revision (2008 Guidelines). Updates on past sampling issues, and current monitoring and sample issues are also discussed. Mitigation monitoring is discussed in Chapter 8.

BWR Sampling Practices

Chapter 8 of the 2008 Guidelines [1] provides recommendations for sampling of key parameters. An EPRI electronic report, “BWR Sampling Summary”, is issued annually to report on sampling practices at the forty-six (46) BWRs that participate in the BWR Chemistry Monitoring Database. The electronic report has been revised since its first issue to include additional timely information (e.g., phosphate monitoring, post-UV analysis, moisture carryover analysis, etc.). The information presented below was compiled from the 2008 electronic report which includes information for forty-five BWRs and does not include information from Ringhals 1 (participation in the BWR Chemistry Monitoring Database began in 2009). A revised electronic report will be prepared in 2009 for issue in early 2010.

Reactor Water Sampling (Non-Metals)

Reactor water sampling practices for non-metallic species are shown in Figure 7-1. All forty-five BWRs routinely report anions including chloride, sulfate, and nitrate. Fewer than one-third of the plants routinely report phosphate, fluoride, and chromate. Forty of the forty-five plants routinely report silica and boron. Sodium is routinely analyzed by 64% of the plants, and about half of the plants routinely analyze for lithium and calcium. Thirty-six of the forty-five plants perform routine tritium analysis.

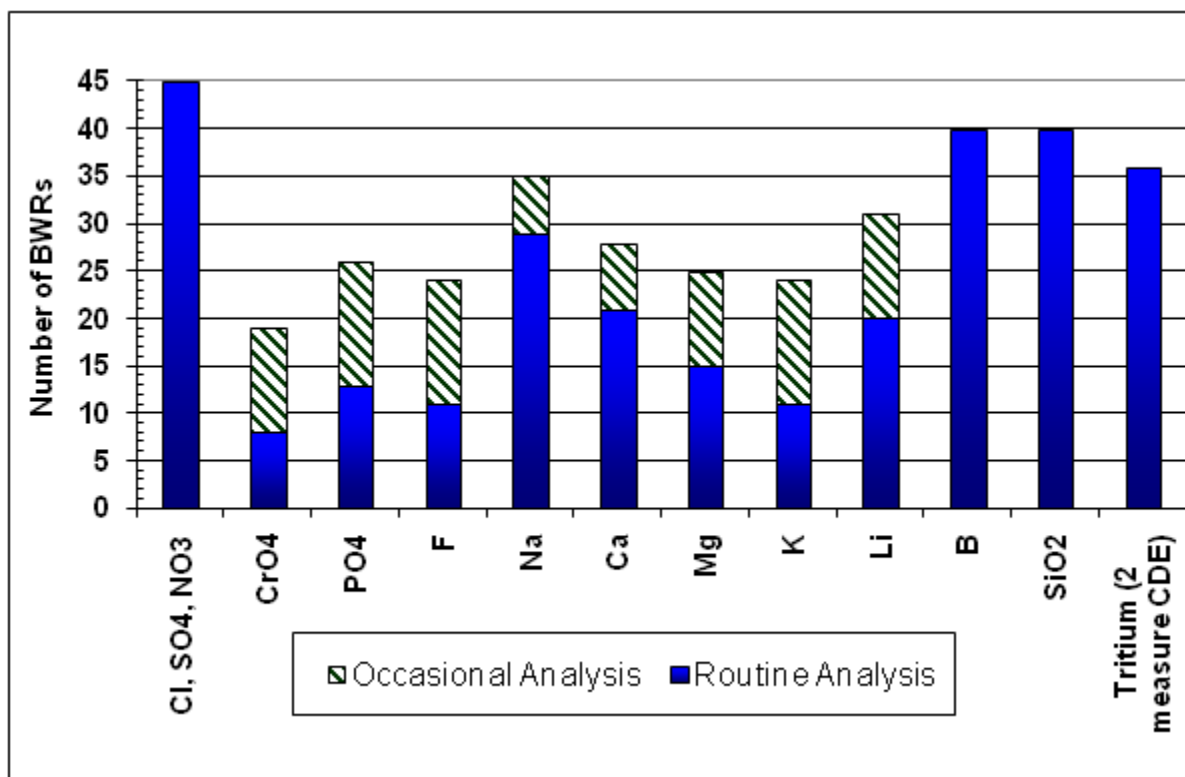


Figure 7-1
Reactor water analysis (non-metals)

Reactor Water and Feedwater Metals Sampling

Reactor water and feedwater metals analysis practices are shown in Figure 7-2. All forty-five BWRs report reactor water and feedwater iron and zinc. Most report reactor water and feedwater copper and nickel. More than half of BWRs perform reactor water and feedwater chromium and cobalt analysis.

Most BWRs use either ICP (inductively-coupled plasma) or XRF (x-ray fluorescence) for analysis of metals other than zinc, as shown in Figure 7-3 and Figure 7-4. Other methods used include atomic adsorption spectroscopy (AA) and ICP/MS (mass spectroscopy). Zinc analysis methods are shown in Figure 7-5 and Figure 7-6. ICP is the predominant method used for reactor water; this method is used at about half of the BWRs. ICP and XRF are the most commonly used methods for feedwater zinc analysis. AA is also used for both reactor water and feedwater zinc analysis, and IC (ion chromatography) is used for reactor water zinc analysis at ten BWRs.

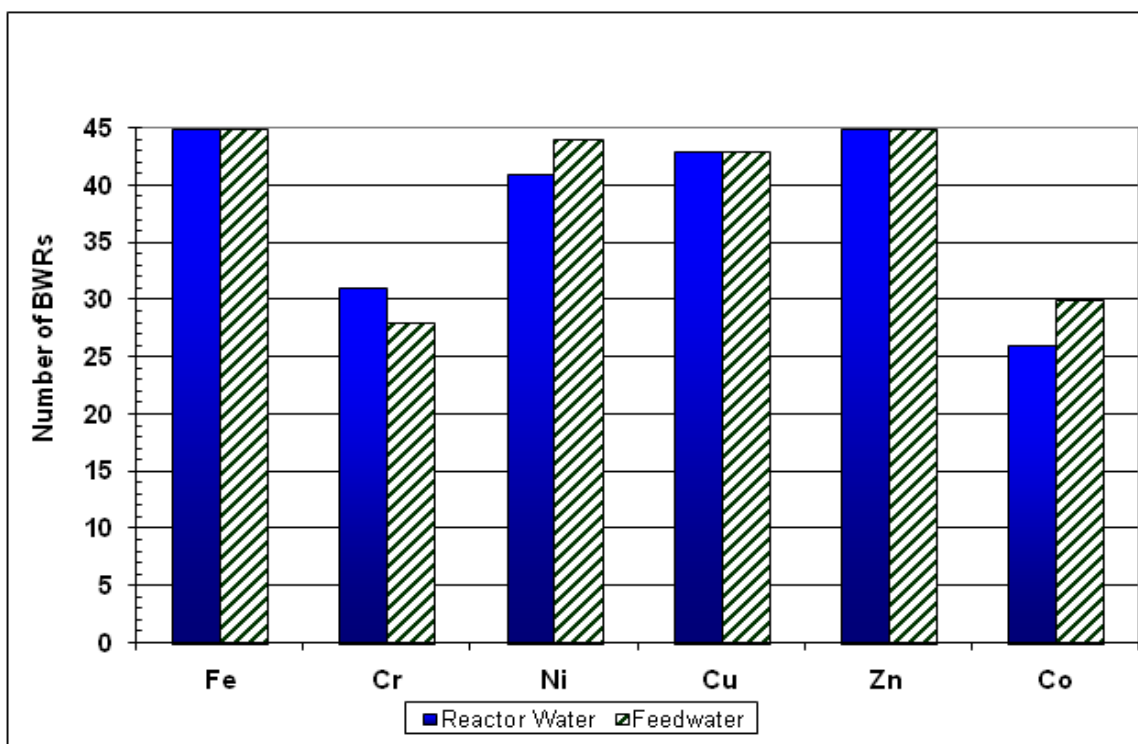


Figure 7-2
Reactor water and feedwater metals analysis

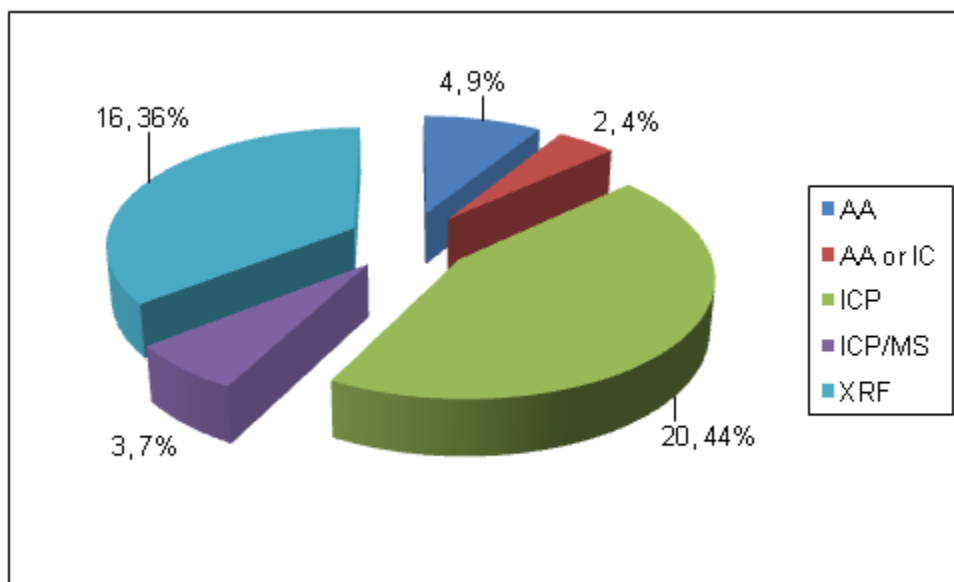


Figure 7-3
Primary analysis method for reactor water metals (other than zinc)

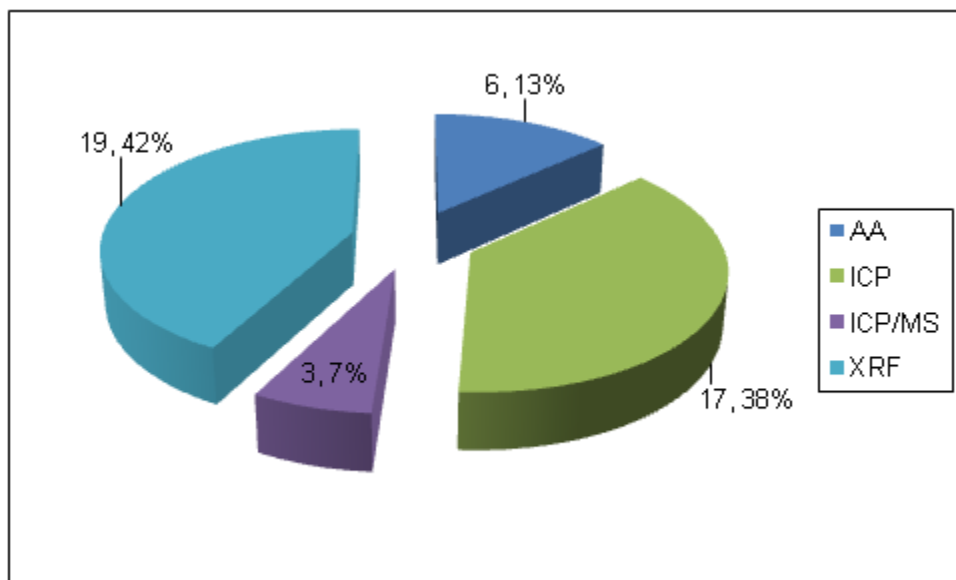


Figure 7-4
Primary analysis method for feedwater metals (other than zinc)

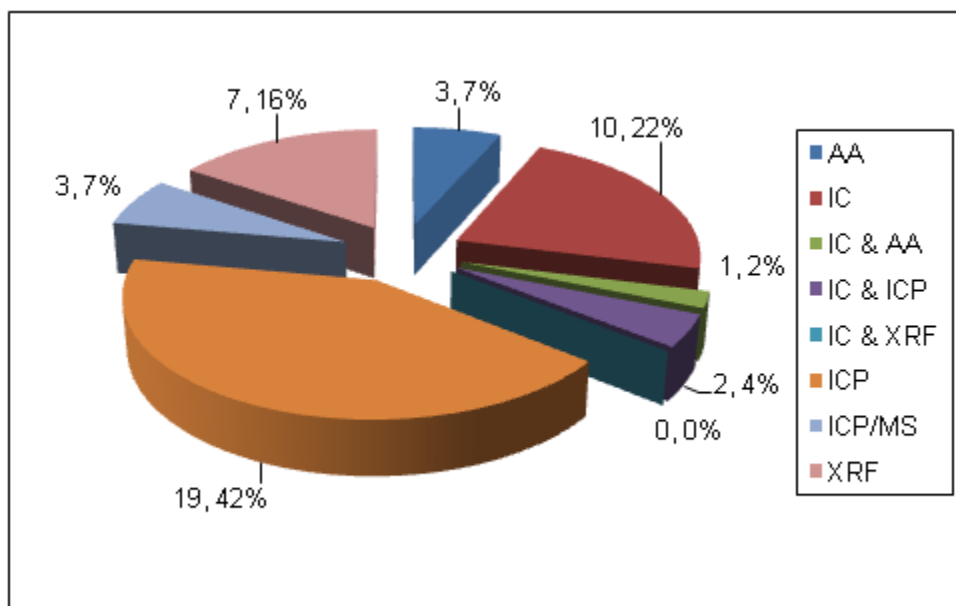


Figure 7-5
Reactor water zinc analysis methods

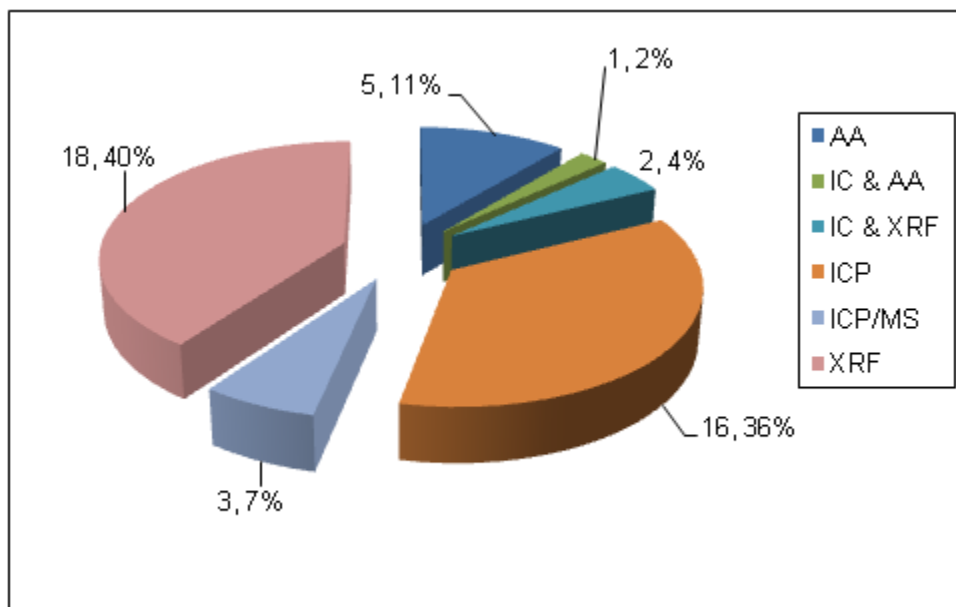


Figure 7-6
Feedwater zinc analysis methods

Sampling Frequencies

Reactor Water

Sampling frequencies for key reactor water parameters are shown in Figure 7-7 through Figure 7-11. Over half of the plants sample and analyze reactor water for chloride and sulfate daily, as recommended in the 2008 Guidelines. Twelve plants sample and analyze reactor water at a frequency of three times per week. The 2008 Guidelines allow less than daily sampling if conductivity and chemistry trends can be used to ensure that Action Levels are not exceeded.

Over 50% of the plants perform fractionated activated corrosion product analysis on a weekly basis. Twenty plants perform reactor coolant zinc analysis on a weekly basis, while eighteen plants perform the analysis more than once per week. Reactor water iron analysis is performed monthly by eighteen plants and weekly by seventeen plants. Twenty-nine of the plants report reactor water lithium results. Three plants perform lithium analysis daily while seven plants perform the analysis monthly.

Feedwater

Feedwater sampling frequencies are shown in Figure 7-12 through Figure 7-14. About 50% of the plants pull sample filters for integrated feedwater iron analysis three times per week while thirteen plants pull and analyze sample filters once per week.

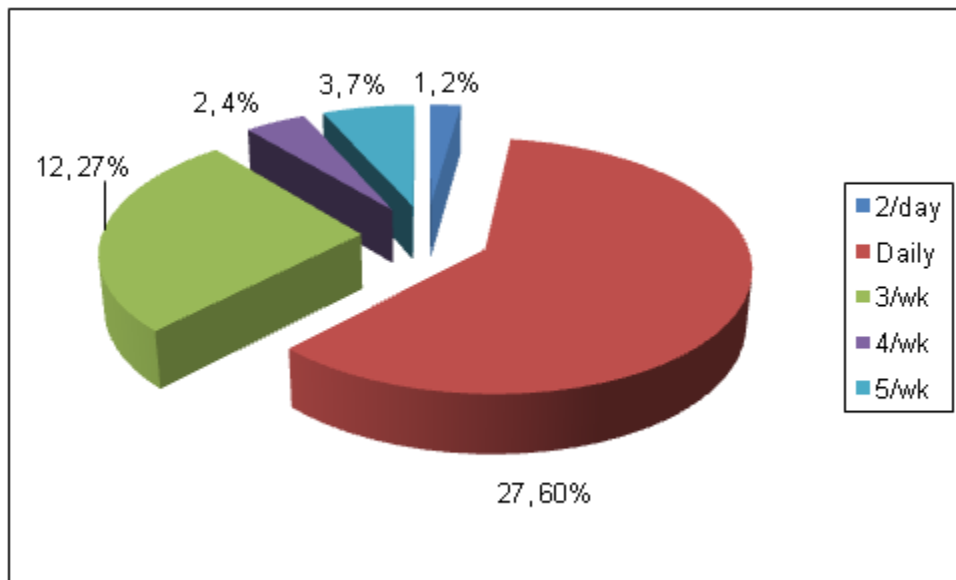


Figure 7-7
Reactor water chloride and sulfate sampling frequencies (recommendation = daily)

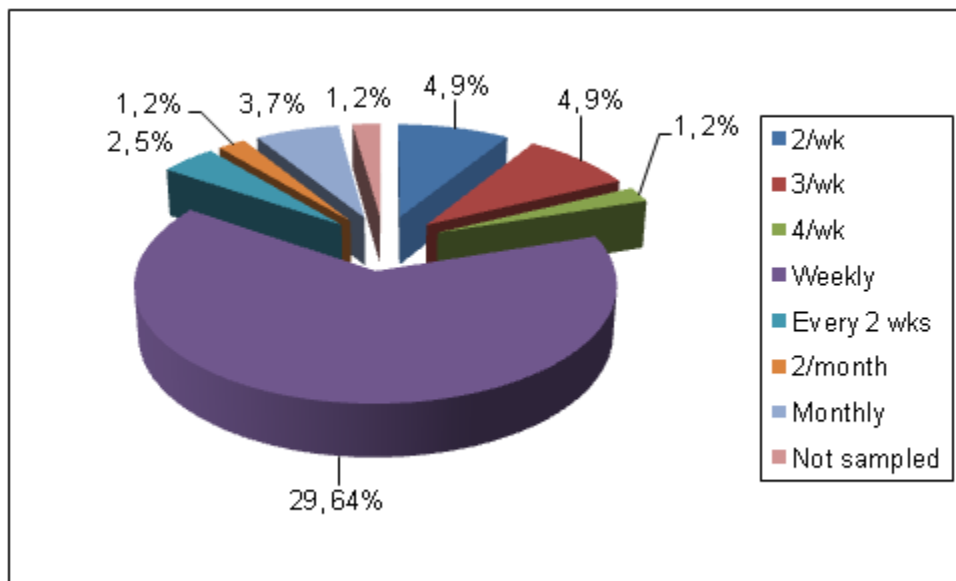


Figure 7-8
Fractionated reactor water Co-60 and Zn-65 sampling frequencies (recommendation = weekly)

About 50% of the plants perform feedwater copper analysis three times per week while thirteen plans perform the analysis once per week. The 2008 Guidelines recommends weekly sampling for plants with CF/Ds and copper alloy main condenser tubes; both BWRs in this category perform sampling three times weekly.

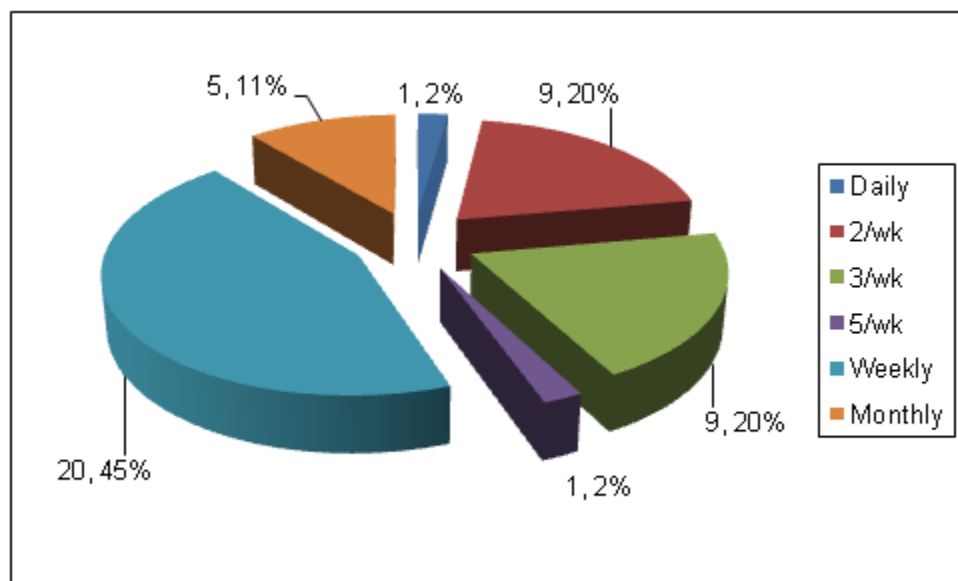


Figure 7-9
Reactor water zinc sampling frequencies ((recommendation = weekly for plants adding zinc or with copper alloy condenser tubes)

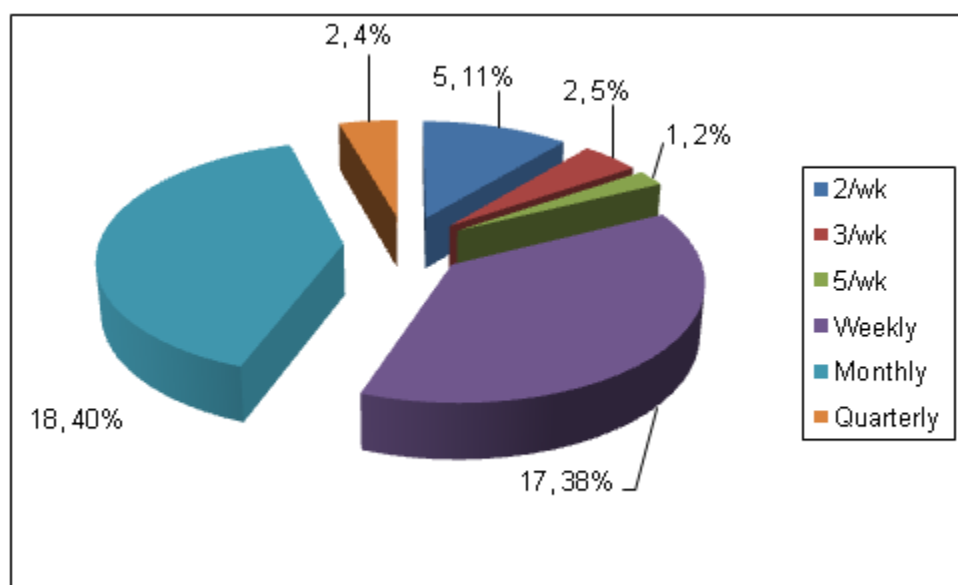


Figure 7-10
Reactor water iron sampling frequencies (recommendation = monthly)

A majority of the plants perform feedwater zinc analysis three times per week while thirteen plants perform the analysis on a weekly basis.

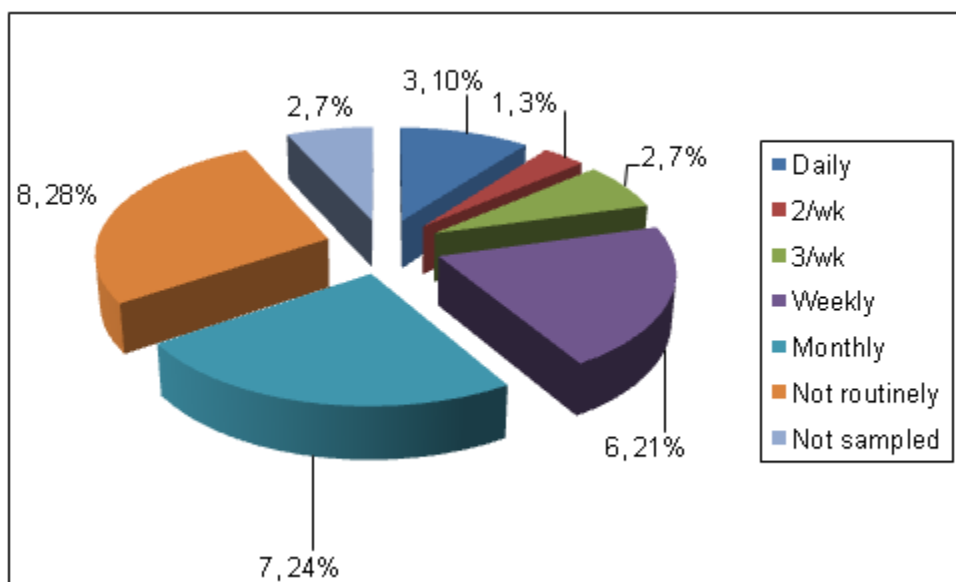


Figure 7-11
Reactor water lithium sampling frequencies

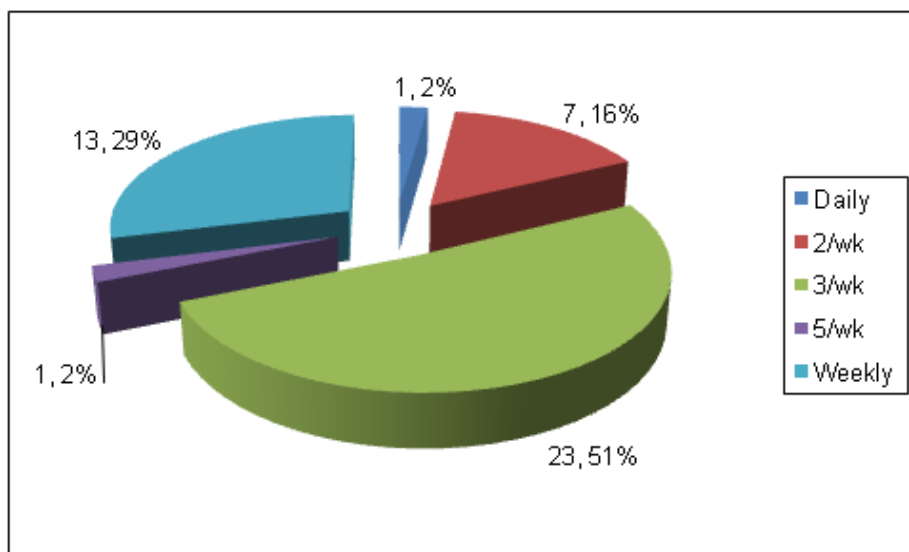


Figure 7-12
Feedwater iron sampling frequencies (recommendation = weekly integrated)

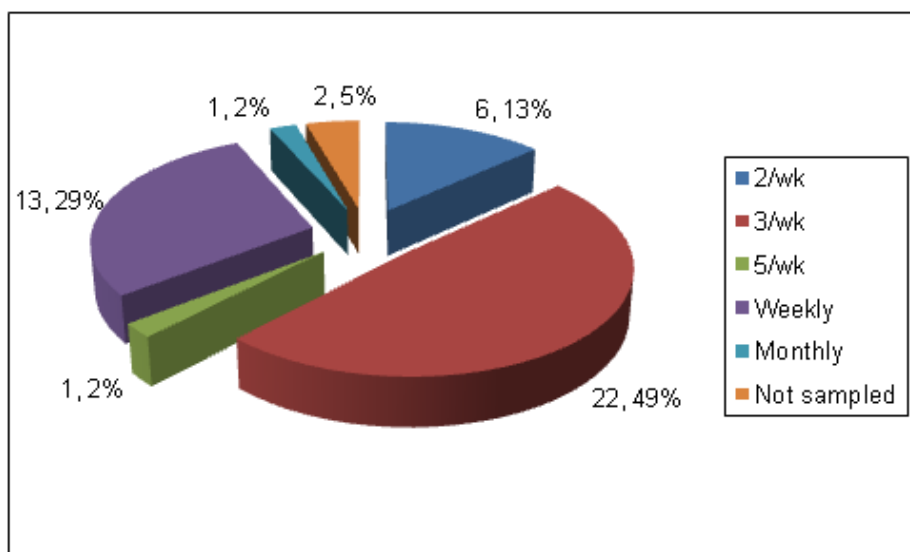


Figure 7-13
Feedwater copper sampling frequencies

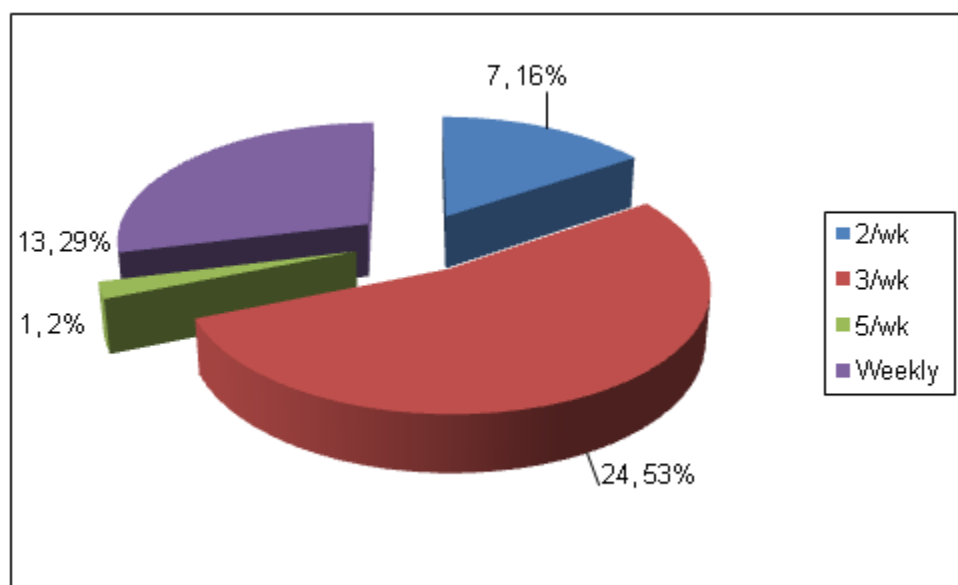


Figure 7-14
Feedwater zinc sampling frequencies (recommendation = weekly for plants adding zinc or with copper alloy condenser tubes)

Post-UV Analysis

Thirty-nine BWRs report having post-UV anions analysis capability. Thirty-seven plants report performing post-UV analysis on Waste Sample Tanks transferred to the CSTs. Of these plants, twenty-eight report performing post-UV analysis on each returned tank. Four BWRs report not performing post-UV analysis of liquid radwaste sample tanks.

Twenty-six BWRs report that post-UV anions analysis is used for makeup water transferred to the CSTs.

Main Steam Line Sampling

Thirty-one BWRs report that a main steam line sample point is present and thirteen report that it is used routinely. At the thirteen plants where the sample point is routinely used, the following parameters are monitored:

- Conductivity – 7 BWRs (5 continuously)
- Na-24 for calculation of moisture carryover – 7 BWRs
- Oxygen – 3 BWRs (1 continuously)
- Hydrogen – 1 BWR

Phosphate Analysis

In the past few years, more plants have initiated analyzing plant water samples for phosphate to address fuel reliability concerns. Recent data also indicate that phosphate is an aggressive anion in accelerating IGSCC [1]. As shown in Figure 7-15, fifteen plants report reactor water phosphate analysis while eighteen plants report performing Waste Sample Tank phosphate analysis. Five plants report phosphate analysis of the hotwell/CPD.

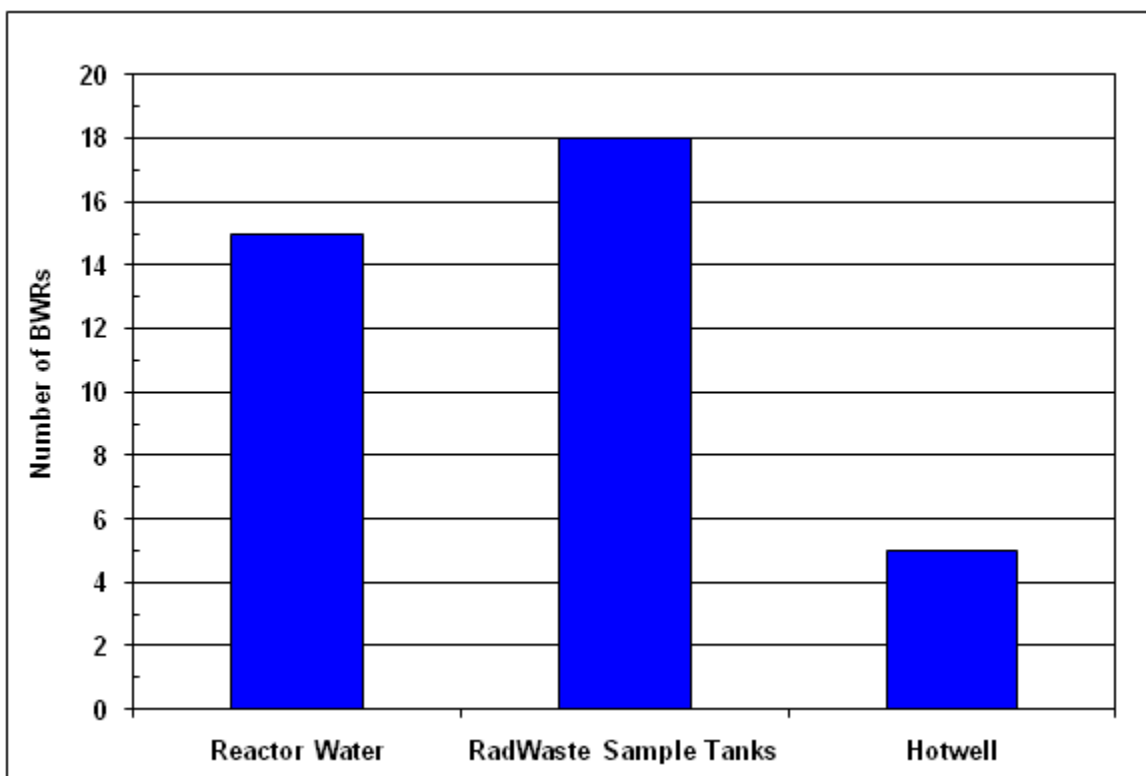


Figure 7-15
BWR phosphate analysis

Sampling Issues

An update on sampling issues reported in previous revisions of the monitoring report and a discussion of recent sampling issues follows.

Feedwater Dissolved Oxygen

The most recent median feedwater oxygen values for forty-five BWRs are shown in Figure 7-16. Some plants use alternate sample points (CPD or CDE) due to noble metals contamination of the feedwater sample lines, and those values are used here when applicable. Feedwater oxygen for all forty-five BWRs was within the recommended range of 30 – 100 ppb for FAC control.

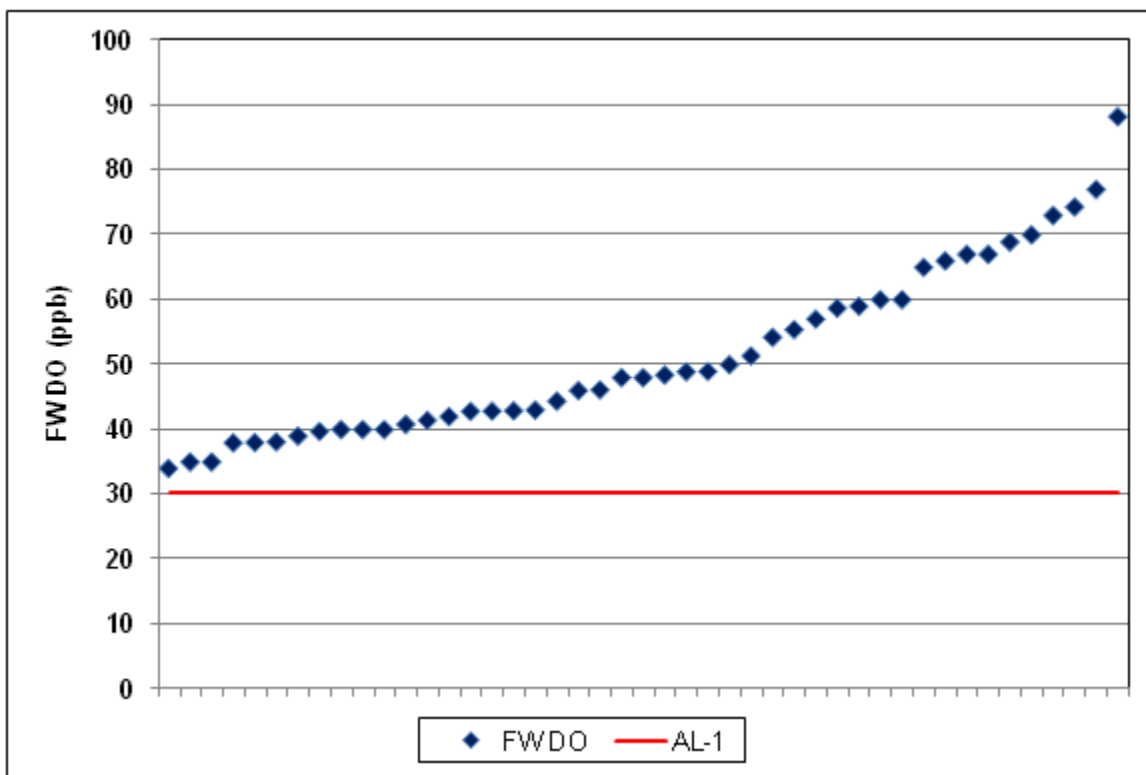


Figure 7-16
Median feedwater dissolved oxygen (most recent one year's data)

Feedwater Sampling Velocity Update

To assure representative sampling, a velocity of 6 ft/sec in the main sample line is recommended [1]. Current feedwater sampling velocities for forty-four BWRs are shown in Figure 7-17. Seven BWRs have velocities of approximately 6 ft/sec, while another thirteen BWRs have velocities exceeding 6 ft/sec. Twelve plants continue to operate with feedwater sampling velocities of <4 ft/sec. Some plants have performed modifications to obtain higher velocities to ensure representative sampling.

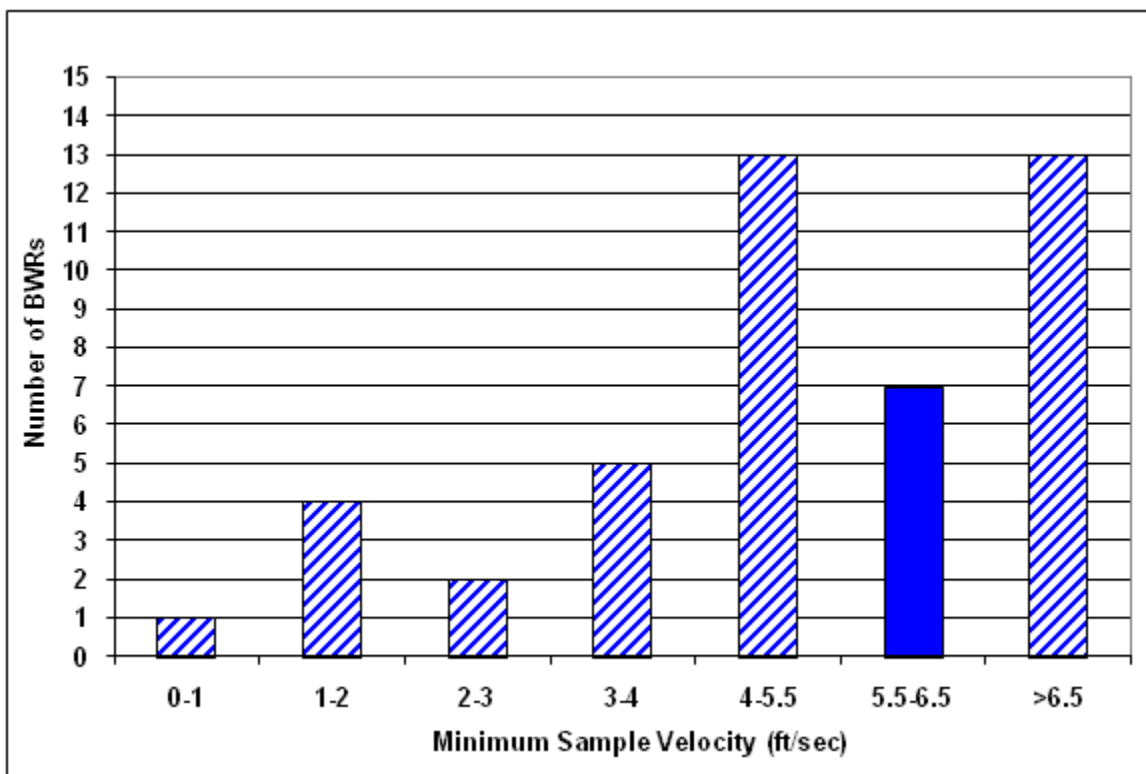


Figure 7-17
Velocity in BWR main feedwater sample tubing (recommended velocity = 6 ft/sec)

Reactor Water Cobalt-60 Analysis

The BWR Water Chemistry Guidelines recommend weekly analysis of reactor coolant activated corrosion products. Using typical analysis methods, “insoluble” (filterable) Co-60 is that which is retained by a 0.45- μm membrane filter and “soluble” (unfilterable) Co-60 is that which passes through the filter. Further differentiation is made between soluble Co-60 captured by cation filter papers and that in the filtrate.

Industry experience cited in the BWR Water Chemistry Guidelines [1] and in the 2005 edition of the BWR Chemistry Monitoring Report [2] shows that using the typical analysis method may not accurately account for the soluble and insoluble fractions. Leibstadt showed that when a small amount of 0.03M NaNO_3 is added to reactor water samples which are then subsequently passed through membrane filters, the apparent soluble fraction increased by about 40%. Testing at some Exelon plants, using membrane filters between 0.1 and 0.45 μm , showed a decrease in the soluble fraction (by as much as 50% at one plant) over the typical sampling method, suggesting the probability that colloidal material is passing through the 0.45 μm membrane filters.

The BWR Water Chemistry Guidelines provide suggestions for sample collection based on PWR experience [1]. The Guidelines note that the most representative samples are obtained when continuously flowing sample lines are used and sample flow is passed through a membrane filter stack (membrane particulate filter and/or cation paper) without exposing the sample to air. Grab sampling with subsequent filtering in the laboratory exposes the samples to air which will precipitate iron hydroxides and soluble radionuclides, leading to higher insoluble fractions.

The Guidelines recommend that plants consider filtering reactor coolant samples at the sample stations without exposure to air in order to improve reliability and reproducibility of data. The main disadvantage of this recommendation is that, at most plants, reactor coolant sample panels and sample sinks are typically located in high radiation areas. Sample filter preparation and subsequent removal of sample filters increases chemistry technician exposure. The more volume passed through the membrane filter stack, the higher the dose rate of the sample filters and the higher the radiation exposure to the technicians. Some BWR stations have decreased the sample volume (thus increasing the lower limit of detection) to limit technician radiation exposure.

Plants were surveyed in 2008 to determine how many are following the recommendation in the Guidelines to filter reactor coolant samples at the sample sink. None of the twenty-four plants that responded to the survey reported that samples are filtered at the sample sink. The reason given was high sample sink/sample panel dose rates. At least one plant has routinely adopted this recommendation since the 2008 survey. About half of the plants responded that they use cation and anion papers as part of the filter stack. At some plants, cation and anion papers are not used for all samples, however.

Moisture Carryover Sampling and Analysis

Moisture carryover (MCO) sampling and analysis is performed for the purpose of assessing the performance of the steam dryer. The method employed at most plants is to perform a gamma isotopic analysis of reactor water and condensate inlet (condensate pump discharge) samples and calculate the percent carryover based on the ratio of Na-24 in the condensate inlet to that in the reactor water. The implementation of extended power uprates and two-year operating cycles has resulted in core operating conditions which favor increased MCO as the operating cycle progresses. Steam separator and steam dryer integrity as well as performance issues (leading to increased MCO) are also concerns. In addition, impurities that may be transported with the steam have been suggested as potential contributors to observations of turbine corrosion.

Most plants, as shown in Figure 7-18, perform moisture carryover analysis. Nineteen plants report performing MCO analysis on a monthly basis while seventeen of the plants perform MCO at least weekly.

In the previous editions of the monitoring report [2, 3], past industry data was presented which showed that MCO is higher at BWR 2 and 3 design plants than at BWR 4 though BWR 6 designs, reflecting improvements in dryer efficiencies in the BWR 4 through BWR 6 designs as well as differences in core and vessel designs.

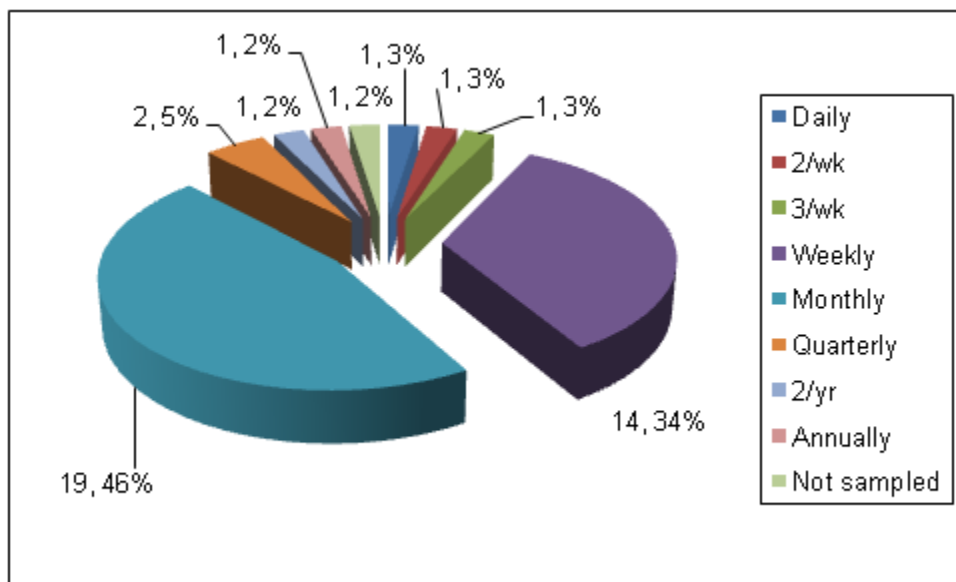


Figure 7-18
Moisture carryover sampling frequency

Recently, there has been an increasing emphasis on MCO as a potential indicator of outage dose rates. Two plants, Pilgrim and Vermont Yankee, have experienced higher than expected dose and contamination levels in steam side equipment (main turbine, MSRs, feedwater heater shells) in recent refuel outages. At Pilgrim, the initial NMCA was performed in the previous outage. During the subsequent operating cycle, the station reported elevated levels of reactor coolant Co-60 as a result of the NMCA and increased MCO towards the end of the cycle. At Vermont Yankee, the station had performed an extended power uprate in 2006 and a subsequent NMCA reapplication in 2008. As at Pilgrim, the noble metal application caused increased coolant Co-60 levels and the station experienced increased MCO towards the end of cycle.

MCO typically increases towards the end of an operating cycle as core flow is increased in an effort to maximize power generation. Operating with maximum core flow at end of cycle and during coastdown would increase the loading on the steam separators and dryers, which would tend to increase moisture carryover. MCO data for Peach Bottom 3, Cycle 16, is shown in Figure 7-19. For the first year of the cycle, MCO was relatively constant, about 0.005%. Levels began to increase at the beginning of the second year of the cycle, corresponding with a core flow increase. In December 2006, about sixteen months into the cycle, MCO was just over 0.02%. MCO then subsequently decreased below 0.02% as core flow decreased. In the last five months of the operating cycle, core flow was on an increasing trend which resulted in MCO increasing to above 0.04%, which is about a factor of eight higher than it was during the first year of the operating cycle.

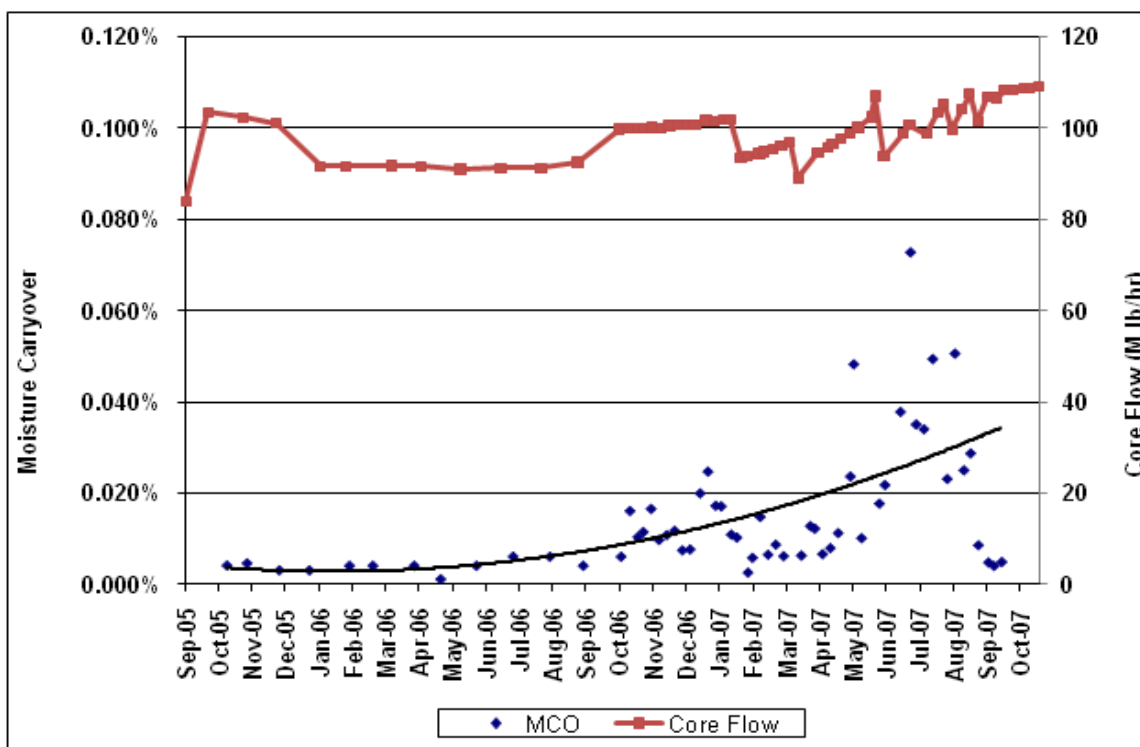


Figure 7-19
Peach bottom 3 cycle 16 moisture carryover

New Methods

In conjunction with an EPRI study, Cooper Nuclear Station has been testing an alternate analytical method for low level ion analysis. The method, capillary electrophoresis (CE), uses an applied external electric field to separate charged species. The migration of ions through the capillary is dependent predominantly on size/charge ratio and the electroosmotic flow of buffer solution through the capillary. The advantages of CE over traditional ion chromatography are lower waste generation and shorter analysis time. Reported LLDs for chloride and sulfate are 0.05 and 0.75 ppb, respectively [4]. Reported LLDs for sodium, calcium and lithium are 10 ppb [5]. Presently, the prototype unit is being tested at the Cooper Nuclear Station Chemistry Training Laboratory. Future work will evaluate the feasibility of online installations and lower LLD for cations.

References

1. *BWRVIP-190: BWR Vessels and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision*. EPRI, Palo Alto, CA: 2004. 1016579.
2. *BWR Chemistry Performance Monitoring - 2005 Edition*. EPRI, Palo Alto, CA: 2005. 1009932.
3. *BWR Chemistry Performance Monitoring - 2007 Edition*. EPRI, Palo Alto, CA: 2007. 1016102.
4. *Capillary Electrophoresis: Analysis of Trace Inorganic Anions in Ultrapure Water*. EPRI, Palo Alto, CA: 2008. 1016612.
5. *Capillary Electrophoresis: Analysis of Trace Inorganic Cations in Ultrapure Water*. EPRI, Palo Alto, CA: 2009. 1018528.

8

MITIGATION MONITORING

The BWRVIP “BWR Mitigation Performance Indicator” (MPI) was developed in 2006 as an example of a mitigation performance indicator that may be implemented in accordance with the requirements of Nuclear Energy Institute (NEI) 03-08. NEI 03-08 considers it a “Needed” requirement for plants to have a mitigation performance indicator, but plants have the option of using the BWRVIP’s MPI or a suitable alternative [1].

A primary component of the MPI is HWC Availability, which is the percentage of the time that ECP is suppressed to ≤ -230 mV (SHE) when reactor water temperature is greater than 200°F with conductivity ≤ 0.3 μ S/cm [1]. During transients, only the time in excess of 24 hours that conductivity exceeds 0.3 μ S/cm needs be considered, and the conductivity can be corrected for the contribution from soluble iron and zinc [1, 2].

Primary parameters for mitigation monitoring include:

- Category 1, HWC-M : Measured ECP
- Category 2, HWC-M, -L, -H: Estimated ECP from BWRVIA model
- Category 3a, NMCA: Catalyst loading and measured ECP
- Category 3b, NMCA: Catalyst loading and measured H₂:O₂ molar ratio

The monitored BWRs and their respective categories are shown in Table 8-1.

Table 8-1
Mitigation categories for monitored BWRs

Category 1 HWC with ECP	Category 2 HWC no ECP	Category 3a NMCA with ECP	Category 3b NMCA no ECP
Chinshan 1, 2	Brunswick 1, 2	Columbia	Browns Ferry 1, 2, 3
Cofrentes	Fermi 2	Cooper	Clinton
Kuosheng 2	Grand Gulf	Dresden 2, 3	FitzPatrick
Ringhals 1	Kuosheng 1	Duane Arnold	Limerick 1, 2 (1)
Santa Maria de Garoña	Monticello	Hatch 1, 2	Nine Mile Point 2*
Susquehanna 1, 2	River Bend	Hope Creek	Perry*
		Laguna Verde 1, 2	
		LaSalle 1, 2	
		Leibstadt*	
		Mühleberg*	
		Nine Mile Point 1*	
		Oyster Creek	
		Peach Bottom 2, 3*	
		Pilgrim	
		Quad Cities 1, 2	
		Vermont Yankee	

Notes

* OLNC.

1. Probes are installed but are not working at either unit.

2. Probe is installed but results are not monitored.

Mitigation Performance Indicator Inputs

The inputs to the MPI for both HWC and NMCA plants are shown in Table 8-2. HWC availability and secondary parameter availability are common inputs for both types of plants. NMCA plants also must include mitigation monitoring system (MMS) availability and catalyst loading. If a plant is using artifacts to monitor catalyst loading, MMS availability is not applicable.

Table 8-2
MPI input parameters [1]

Parameter	HWC Plants	NMCA Plants
HWC Availability	yes	yes
Availability of Two Secondary Parameters	yes	yes
Secondary Parameters	Reactor water DO Reactor water H ₂ Feedwater H ₂ concentration or flow rate Main steam line radiation level Main steam DO	Reactor water DO Feedwater H ₂ concentration or flow rate Measured molar ratio Molar ratio from model (model should bound operating conditions for the current cycle)
Catalyst Loading	not applicable	yes
Mitigation Monitoring System Availability	not applicable	yes (not applicable for plants using artifacts to monitor catalyst loading)

Mitigation Performance Indicator Colors

The significance and definitions of the four MPI colors are shown in Table 8-3. Both the green and white categories indicate satisfactory performance with no corrective action required. Yellow indicates that goals are not being consistently met and improvement is needed. A red indicator indicates unsatisfactory performance, and issuing a Condition Report is suggested to communicate and facilitate resolution of problems. A fifth color, gray, is used to denote inactive status or when data are not available or applicable.

The criteria for each individual performance indicator (PI) for HWC and NMCA plants are shown in Table 8-4 and Table 8-5, respectively. The criteria for the overall MPI are listed below [1]:

- The MPI is green only when all the applicable PIs are green.
- If any PI is White, the MPI is White.
- If any PI is Yellow, the MPI is yellow.
- If any two PIs are Yellow, the MPI is Red unless one Yellow PI is due to secondary parameter availability and the primary indicator is still functional, in which case the MPI remains Yellow.
- If any PI is Red, the MPI is Red.
- For Category 1 plants (HWC with ECP monitoring), if there is only one secondary parameter available the MPI is Yellow, and if there is no secondary parameter available, the MPI is Red.
- For Category 2 plants (HWC without ECP), if there is only one secondary parameter available, the MPI is Red.

A new set of criteria are under development for plants that have implemented OLNLC. At these plants, low catalyst loading is offset by application frequency, and the need for monitoring via coupon analysis may no longer be applicable. In addition, relaxed HWC Availability goals for these plants are being considered.

Table 8-3
MPI colors [1]

Color	Significance	Definition	Corrective Actions
Green	Excellent / Significant Strength	A strength, exceeding expectations; positive trend; good performance relative to industry	No corrective action required.
White	Satisfactory	Meeting expectations; within goals; positive trend; good performance relative to the industry	No corrective action required.
Yellow	Needs Improvement	Not consistently meeting expectations and goals (nominally and/or frequently below); negative trend; weak performance relative to industry	Ensure plan in place to improve performance. Increase management oversight and awareness. Communicate expectations and plans.
Red	Unsatisfactory / Significant Weakness	Not meeting expectations and goals (significantly and/or consistently below); significant negative trend; poor performance relative to industry	Perform an assessment of current improvement plans to ensure adequacy. Ensure site management awareness and that appropriate resources are assigned. Communicate expectations and plans. Increase oversight/monitoring frequency. Consider writing a Condition Report to facilitate resolution.

Table 8-4
HWC mitigation performance indicator [3]

	Must be in Spec for all	Any One Parameter	Any One Parameter	Any One Parameter or 2 Yellow Parameters
HWC Availability	≥ 95 %	≥ 90%, < 95%	≥ 80%, <90%	< 80%
2 Secondary Parameters Availability	≥ 95 %	≥ 90%, < 95%	≥ 80%, <90%	< 80% and no primary indicator, otherwise stays yellow

Notes

Cat. 1 plant losing ECP should consider Yellow PI.

Cat. 2 plant may be Yellow if no sister plant with ECP, as there is no proof of mitigation.

Table 8-5
NMCA mitigation performance indicator [3]

	Must be in Spec for All	Any One Parameter	Any One Parameter	Any One Parameter or 2 Yellow Parameters
HWC Availability	$\geq 98\%$	$\geq 95\%, < 98\%$	$\geq 90\%, < 95\%$	$< 90\%$
Catalyst Loading or EOC Predicted Catalyst Loading, $\mu\text{g}/\text{cm}^2$	≥ 0.15	< 0.15 to ≥ 0.125 ppb	< 0.125 to ≥ 0.10 ppb	< 0.10
MMS Availability (1)	$\geq 90\%$	$\geq 80\%, < 90\%$	$< 80\%$	N/A
2 Secondary Parameters Availability (2)	$\geq 95\%$	$\geq 90\%, < 95\%$	$\geq 80\%, < 90\%$	$< 80\%$ and no primary indicator, otherwise stays yellow

Notes

1. If a plant is monitoring catalyst loading on artifacts and not using an MMS, only then would this indicator be N/A.
2. If a primary indicator is unavailable and 2 secondary parameters are unavailable, indicator is RED.

Mitigation Performance Summary

Mitigation performance for monitored BWRs for which complete cycle data were available is discussed in this section. Data for the first cycle with HWC at Leibstadt, which recently transitioned from NWC to OLNC, were not yet available.

HWC Availability

HWC availability for the last completed cycle for forty-five BWRs is shown in Figure 8-1. Eight of fifteen BWRs with HWC and twenty-nine of thirty BWRs with NMCA achieved green or white status for HWC availability. HWC availability was Red at only three BWRs, all HWC plants. Availability at HWC plants may be impacted by the need to shut down or turn down hydrogen injection to perform maintenance work in areas affected by main steam line radiation.

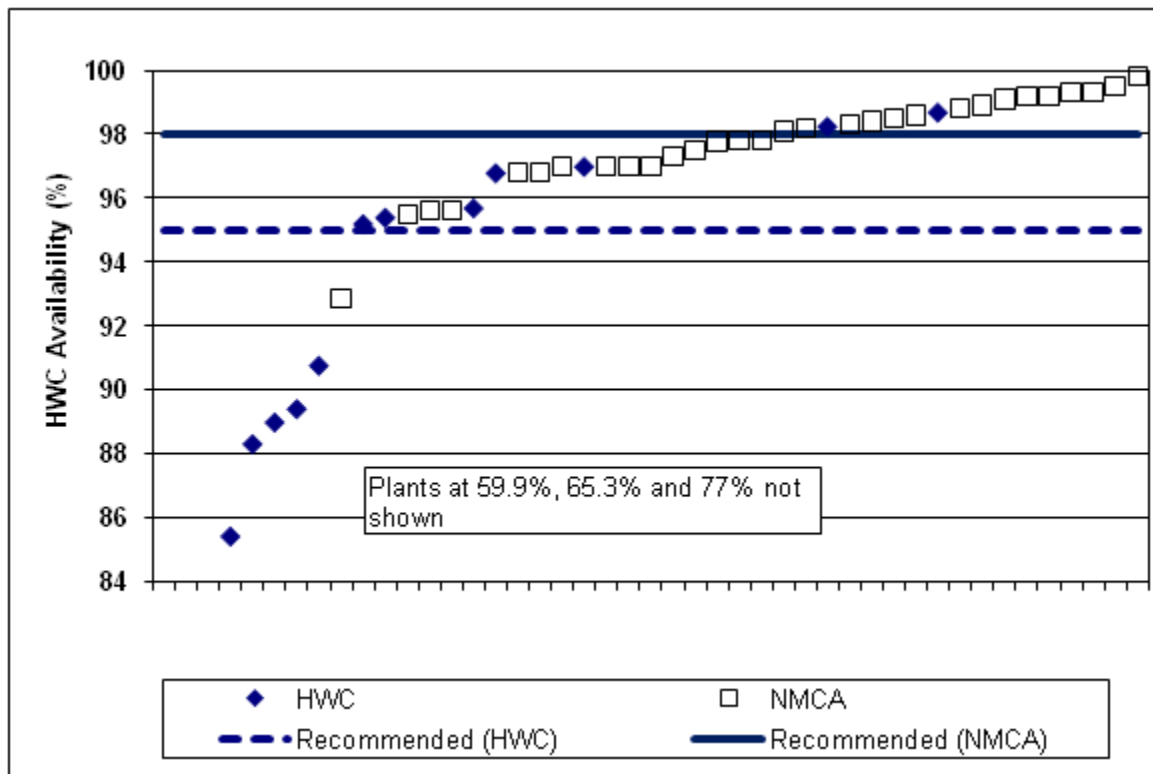


Figure 8-1
HWC availability for last completed cycle

HWC availability statistics for cycles started in the years 2000 – 2007 are shown in Figure 8-2 and Figure 8-3. Over these years, there was a significant increase in the percentage of BWRs with cycle average HWC availability greater than 95%, from 37.5% in 2000 – 2001 to over 80% since 2004. Implementation of NMCA and equipment modifications to improve system reliability and/or to allow hydrogen injection at lower power levels are contributors to the improved availability.

Average HWC availability for HWC-M plants has remained relatively constant at about 90%. Values for the later years are skewed slightly low by three plants with low availability; the average HWC availability for U.S. plants was 92.4% in 2004 – 2005 and 93.4% in 2006 – 2007.

Average HWC availability for NMCA plants increased from 95.4% in 2000 – 2001 to greater than 97% in 2002 on.

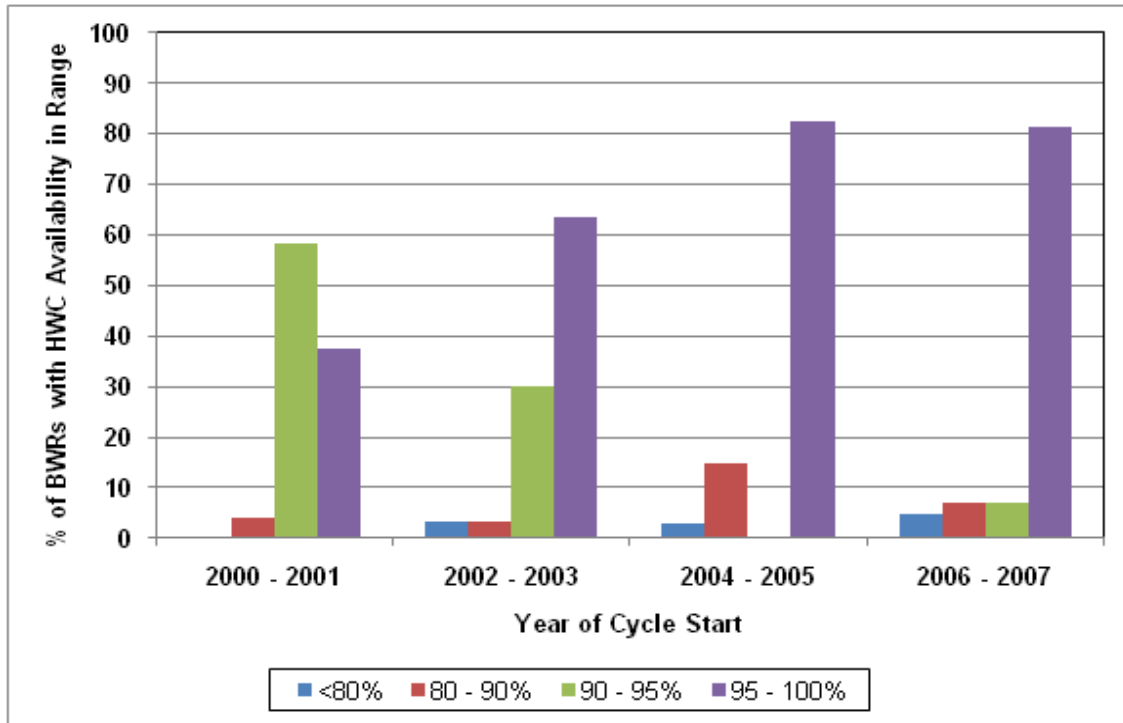


Figure 8-2
HWC availability by cycle start date (2000 – 2007)

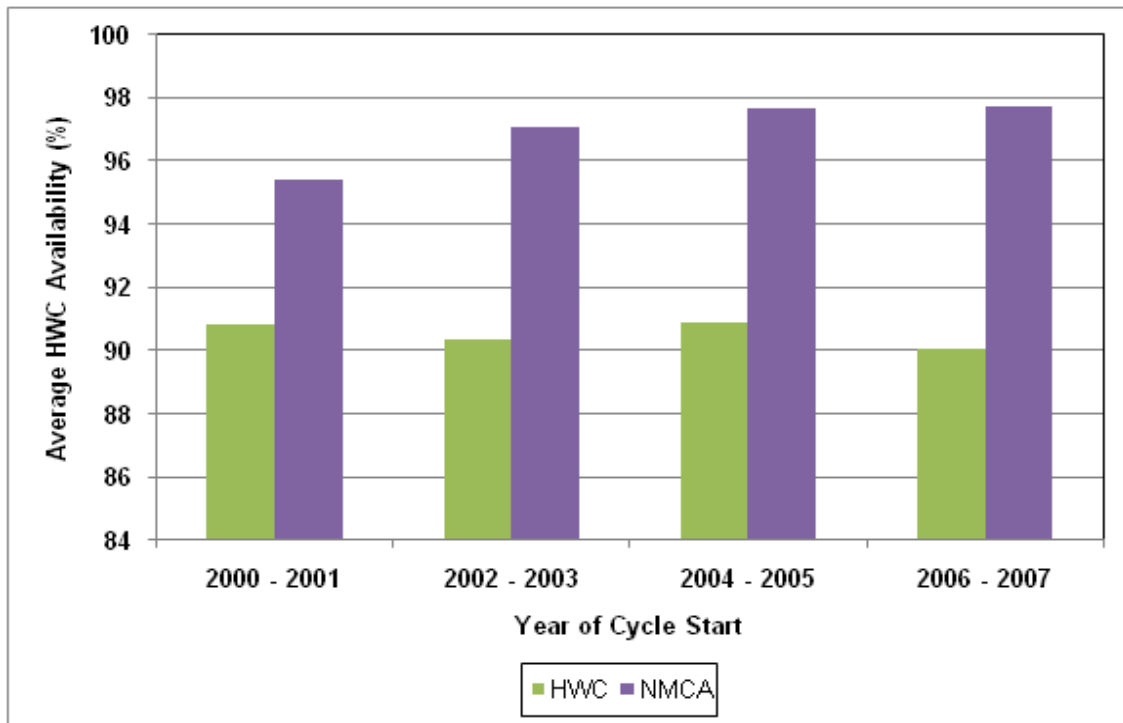


Figure 8-3
Average HWC availability for HWC and NMCA plants (2000 – 2007)

Secondary Parameter Availability

Twenty-eight BWRs with NMCA reported secondary parameter availability. Twenty-five of these reported availability as 100% and the other three plants' availability was 99% or greater. Thirteen of fifteen HWC plants reported secondary parameter availability as 100%. The other two BWRs have no sister plant with ECP against which the secondary parameters can be benchmarked. Although actual secondary parameter availability was 100% at these two BWRs, the secondary parameter PI is "Yellow" by definition.

MMS Availability

Mitigation monitoring availability for twenty-five BWRs is shown in Figure 8-4. Only four of the BWRs who reported data did not meet the "green" goal of 90% availability. Three BWRs were in the white category and only one was in the yellow category.

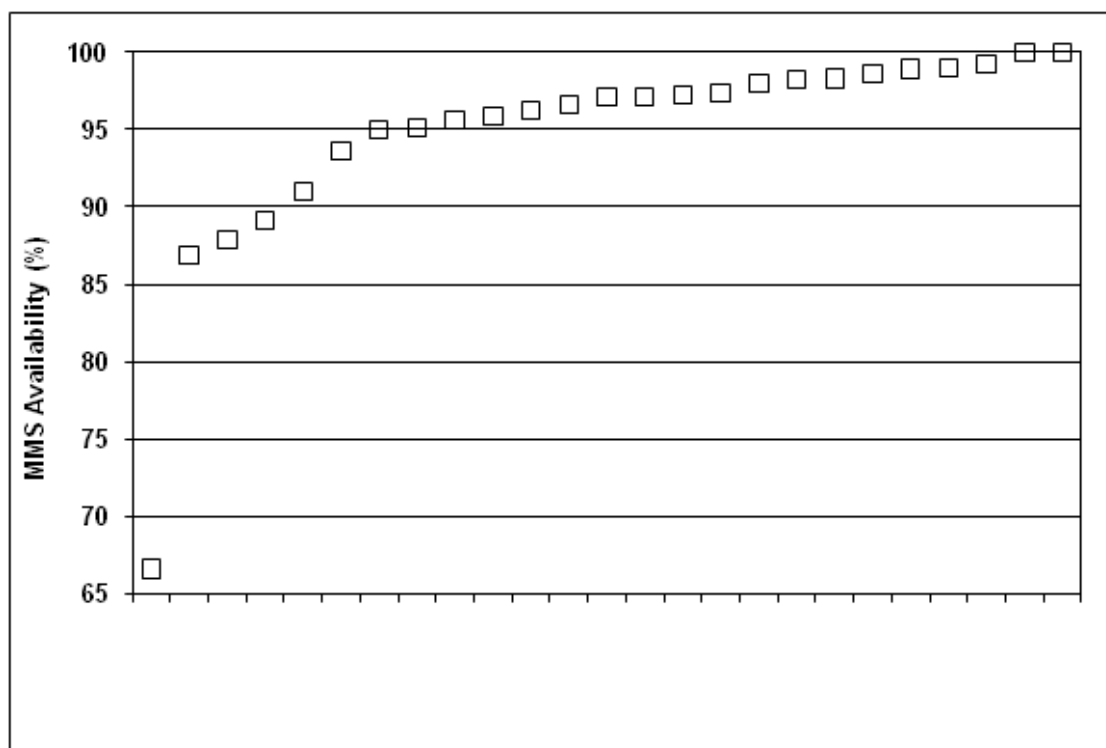


Figure 8-4
MMS availability for last completed cycle

Catalyst Loading

Reported catalyst loading results for twenty-two BWRs are shown in Figure 8-5. The results vary from 0.36 to 2.13 $\mu\text{g}/\text{cm}^2$. In general, the higher results are for plants with a recent initial NMCA or reapplication.

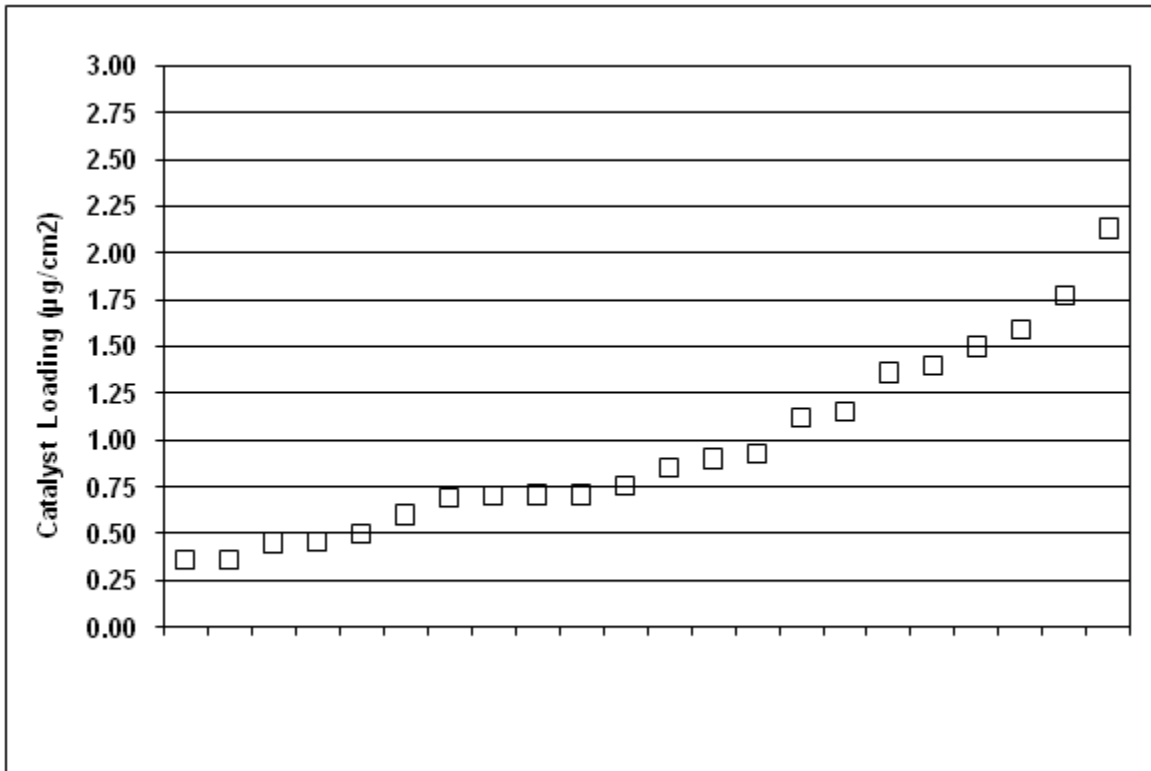


Figure 8-5
Catalyst loading for last completed cycle

Mitigation Performance Indicator

The overall MPI for the last completed cycle at forty-three BWRs is shown in Figure 8-6.

The overall MPI was green or white for twenty-six of twenty-eight (93%) of BWRs with NMCA and for six of fifteen (40%) of BWRs with HWC.

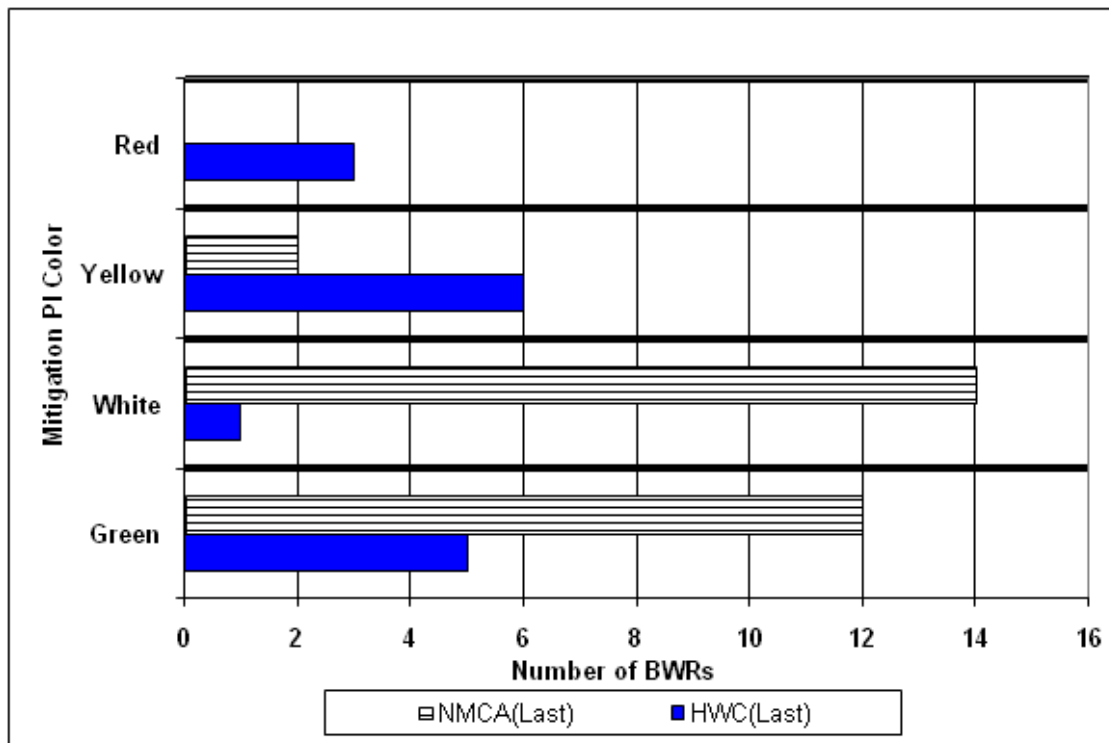


Figure 8-6
MPI for last complete cycle

Factors Influencing Hydrogen Availability

The power level at which hydrogen may be injected has an impact on cycle availability, as shown in Figure 8-7. In general, the plants with highest cycle availability were those with higher availability during the first month of the cycle. The power level at which hydrogen injection may be started is shown in Figure 8-8. Currently, about 44% of BWRs begin hydrogen injection when reactor power is less than 25%, and 80% begin hydrogen injection when reactor power is less than 50%. Early HWC (EHWC) is being evaluated by EPRI to inject hydrogen during heatup and low power operation during startup before feedwater hydrogen injection is available to minimize crack growth during these periods. Work toward a demonstration of EHWC at a U.S. plant that has been treated with noble metals is in progress, with Peach Bottom 2 targeted for the startup from the fall 2010 refueling outage. Hydrogen injection during startup has been demonstrated at some Japanese plants that have not received noble metal applications.

Prior to June 2009, plants were requested to provide information on the number of planned and unplanned HWC system trips and turndowns. Cycle average hydrogen availability is plotted against the number of reported HWC system trips during the cycle in Figure 8-9. The data indicate no correlation between the cycle availability and the number of trips, suggesting that most trips are of short duration and do not greatly affect availability. At the BWRVIP Mitigation Committee Meeting in June 2009, it was decided that tracking of number of trips was no longer required as an activity, but plants may continue to do so for information only.

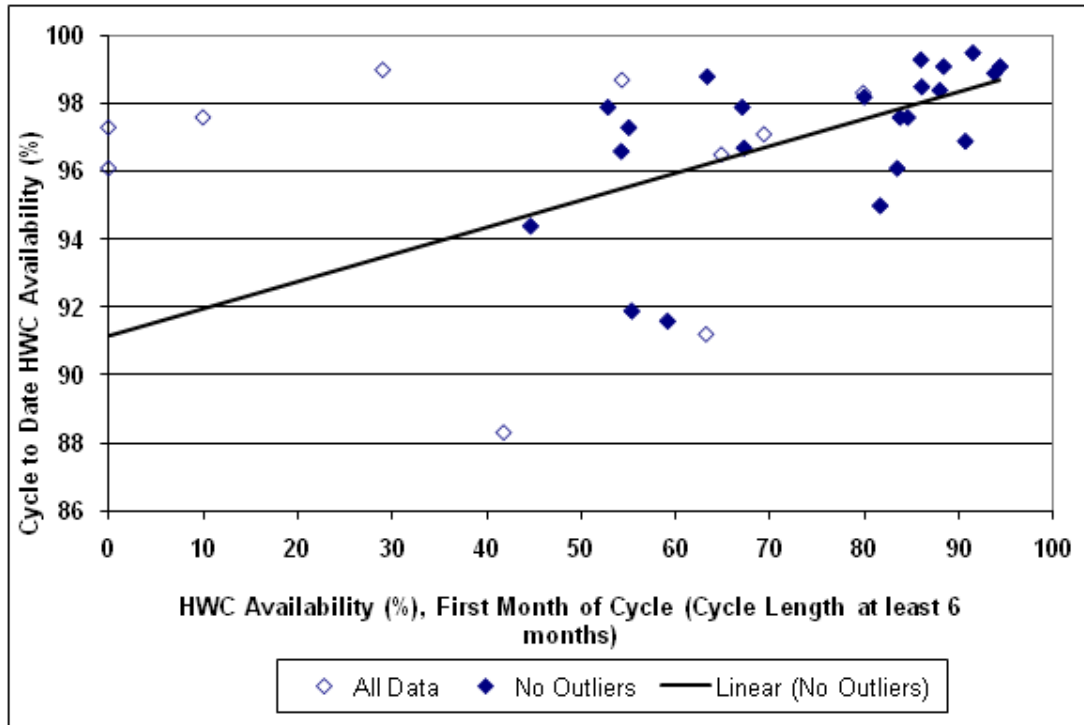


Figure 8-7
Cycle HWC availability vs. first month HWC availability [4]

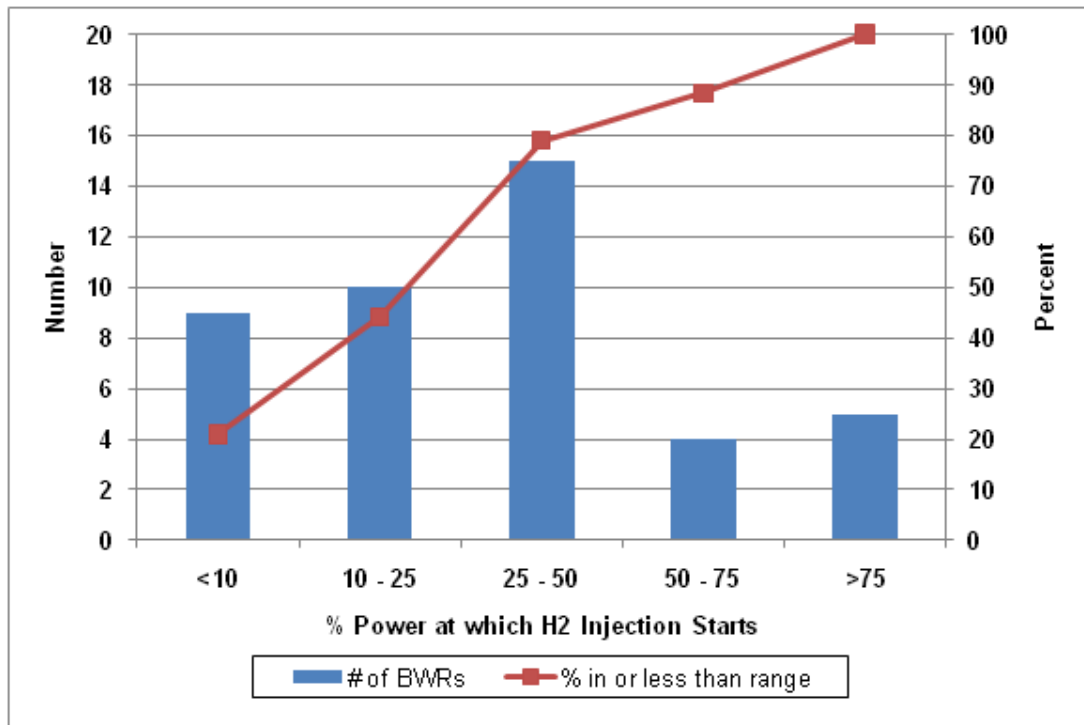


Figure 8-8
Power level at which hydrogen inject starts

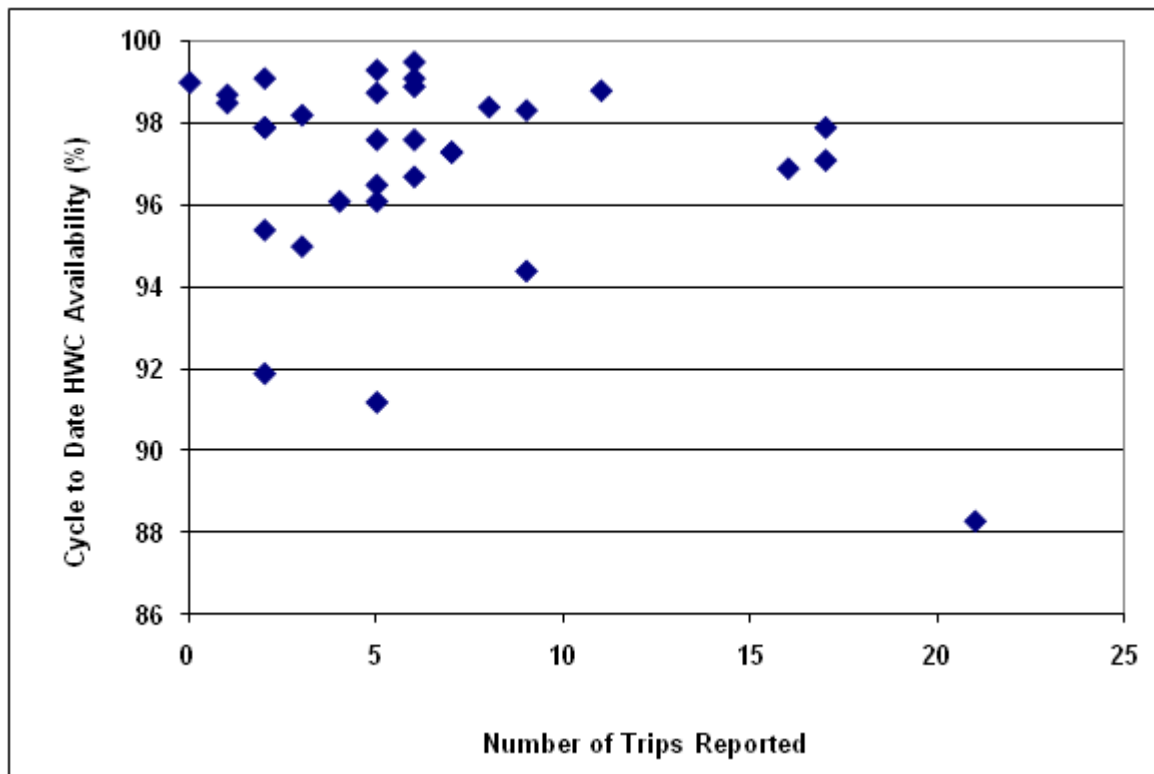


Figure 8-9
HWC availability vs. number of HWC trips [4]

Conclusion

BWRs continue to strive to achieve high HWC availability to mitigate IGSCC. Improvements have been made in system reliability and in the ability to inject hydrogen at lower reactor power. EHWC may be a future strategy to improve HWC availability at startup.

References

1. BWRVIP Letter 2006-345. BWRVIP “BWR Mitigation Performance Indicator”. July 19, 2006.
2. *BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – 2008 Revision*. EPRI, Palo Alto, CA: 2008. 1016579.
3. BWRVIP Letter 2006-408. Errata to BWRVIP “BWR Mitigation Performance Indicator”. September 7, 2006.
4. “BWR Performance Indicator Database”, BWRVIP Mitigation Committee Meeting, December 2008.

9

CONDENSATE FILTER EXPERIENCE

This chapter provides an overview of the current status of BWR condensate filtration. More detailed analysis is available to EPRI Condensate Filter Users Group members. The group's mission is to facilitate the improvement of high efficiency iron removal condensate filter technology through evaluation of septa performance and communication of information concerning filter septa design, performance, modification, and operating experience.

Filtration System Design

A number of basic design differences exist among BWR condensate filtration systems. These differences are discussed below and a matrix of BWR condensate filtration system design attributes can be found in Table 9-1.

Tubesheet Location

With the exception of the HFF system at Oyster Creek, condensate filter vessels are designed with either a top or bottom tubesheet. Detailed descriptions of these systems are found elsewhere [1]. Recent prefilter retrofits, except at Oyster Creek, have all been of the top tubesheet design. Most filter demineralizer vessels are of the bottom tubesheet design.

Backwash Type

Particles collected on the filter media during the service run are removed by backwashing the septa. The effectiveness of the backwash can have a major impact on filter performance and service life of the septa. There are two basic backwash classifications commonly used for cleaning septa in BWR condensate filters: steady state and non-steady state.

Graver's "Mod III" backwash method is the only steady state method in use in current BWR applications, and is used only with bottom tubesheet filter vessels. Four variations of the non-steady state method are in use: "Air Surge"; "Air Bump"; "Air Cannon"; and "Slam Dunk". Backwash procedures vary from manufacturer to manufacturer and from plant to plant. The methods above have been described in detail in a previous report [2].

The hollow fiber modules in the HFF vessels at Oyster Creek are not backwashed, but are cleaned using a method consisting of a steady flow of air and small volumes of water to shake the fibers to remove the solids from the outside of the fibers and convey them to the radwaste system.

"Air Bump" and "Air Surge" with Kinetic Conversion methods for top tubesheet vessels with pleated septa have been tested on a pilot scale but are not currently used in full scale BWR application.

Table 9-1
BWR condensate filtration system design attributes

Station	Tubesheet Location	Backwash Type	Automatic Flow Balancing Available	Flow Balancing Used	Septa Attachment Type (Bottom Tubesheet Vessels, where Known)
Filter/Demineralizers					
Browns Ferry	Bottom	Air Surge	Yes	Manual	SealFast; guide rods
Cofrentes	Top	Air Cannon	Yes	Manual	O-ring with bottom support grid (Degremond)
Columbia	Bottom	Air Surge	Yes	Manual	SealFast; guide rods
Cooper	Bottom	Steady State	Yes	Manual	SealFast
Duane Arnold	Top	Air Bump	No	None	
Fermi 2	Top	Air Bump	No	Manual	
Hatch	Bottom	Air Surge	Yes	Automatic	Cast adapter with guide rod
Leibstadt	Bottom	Air Surge	No	Manual	Christ AG (guide rod with o-ring and bayonet catch)
Monticello	Bottom	Air Surge	Yes	Automatic	Cast adapter
Muehleberg	Bottom	Steady State	No	Manual	Guide rod with bayonet fitting, rubber seals at top and bottom; SealFast in some vessels
Peach Bottom	Bottom	Air Surge	Yes	Manual	SealFast; full flow guide rods
Quad Cities	Bottom	Air Surge	Yes	Automatic	SealFast; full flow guide rods
Ringhals 1	Bottom	Air Surge		Manual	
Vermont Yankee	Bottom	Air Surge	Yes	Automatic	SealFast

Table 9-1
BWR condensate filtration system design attributes (continued)

Station	Tubesheet Location	Backwash Type	Automatic Flow Balancing Available	Flow Balancing Used	Septa Attachment Type (Bottom Tubesheet Vessels, where Known)
Prefilters					
Brunswick	Bottom	Steady State	Yes	Automatic	
Clinton (BPF4)	Top	Slam Dunk 5 Air Bump 1	No	None	
Dresden	Top	Advanced Slam Dunk	No	None	
Hope Creek	Top	Slam Dunk	Yes	None	
Laguna Verde	Top	Air Bump	Yes	None	
LaSalle	Top	Air Bump	No	None	
Limerick	Bottom	Air Surge	Yes	Automatic	
Nine Mile Point	Top	Air Bump	No	None	
Oyster Creek	Top & Bottom	Air Scrub	No	None	
Perry	Top	Air Bump	Yes	Automatic	
River Bend	Top	Air Bump	No	Manual (if desired)	
Santa Maria de Garona	Top	Air Bump	No	Manual	
Susquehanna	Top	Air Bump	Yes	Automatic	

Flow Balancing

Flow balancing is desirable to prevent large discrepancies in flow among vessels caused by differences in piping configuration and by septa of various ages and degrees of fouling. Flow balancing is accomplished by manipulation of CF/D effluent valves. Optimal CF/D effluent valve settings result in uniform flow distribution among the CF/Ds and the achievable minimum CF/D system dP. Appropriate settings provide uniform flow distribution among the CF/Ds and a system dP that does not cause the system bypass valve to open. Inappropriate valve settings could result from instrument errors or transient system dP changes during the short time required for system flow to equilibrate after vessel effluent valve setting adjustments.

For effective flow balancing, it is desirable that the effluent valve of the vessel with the highest sum of piping and septa resistance to flow be at least 85% open. A simple technique is setting all effluent valves at 85% and then adjusting the valves on the vessels with high flow.

There are advantages and disadvantages to both automatic and manual flow balancing systems. The implementation of PLC-based logic has made automatic systems more responsive to fluctuations in plant conditions.

Appropriate manual flow balancing procedures can maintain a constant low operating system dP in the absence of an automatic flow balancing system. Procedures should ensure that one valve is at least 85% open, and that adequate time be allowed for system equilibration between valve manipulations. Careful monitoring of system dP during any vessel or valve manipulation is essential to avoid disturbances in flow that could cause actuation of the system bypass valve.

Automatic flow balancing is used at eight BWR stations. Manual flow balancing is used at eleven stations, five of which have automatic flow balancing capability. Flow balancing is not used at eight stations, two of which have automatic flow balancing capability.

Septa Attachment Methods

A reliable septa attachment method is particularly important for plants with CF/Ds, as a secure seal is needed to prevent precoat material transport to the vessel effluent, and subsequently to the reactor, where thermal decomposition/desulfonation of cation resin can contribute to reactor water sulfate excursions.

Many stations with bottom tubesheet vessels have replaced the original septa attachment hardware with newer hardware types for increased reliability and ease of disassembly and reassembly for ALARA considerations. Removable hardware has been replaced with permanent hardware for lower future material costs and lower exposure during element change outs. Cast adapters have been replaced with SealFast™ adapters, which provide a threaded attachment to connect the bottom of the filter septum to the tubesheet fitting. More details on septa attachment methods can be found elsewhere [1, 3, 4, 5]. Currently, half of stations with CF/Ds use SealFast hardware in all vessels.

Browns Ferry eliminated the tubesheet adapter altogether; the polypropylene septa end fittings were threaded directly onto the stainless steel tubesheet fitting. The top of the tubesheet fitting contacts the inner ring at the bottom of the septum, creating a liquid-tight seal. Beginning in 2005, numerous septa unlatching events occurred at Browns Ferry, more often at Unit 2 than at Unit 3. The events occurred after backwash/precoat operations or after septa replacement. The station has installed Graver SealFast™ hardware in all vessels. The impact on reactor water sulfate is discussed later in this report.

At Vermont Yankee, after fat yarn septa were installed to provide additional surface area after EPU, resin leakage was experienced during body feed of cation-rich precoat material for copper control. The likely leak path was through the septa end fittings. The station replaced all yarn wound septa with Graver DualGuard I septa with SealFast adapters and full flow guide rods. The impact on reactor water sulfate is discussed later in this report. Feedwater copper was also reduced because the station was able to use cation-rich resin for soluble copper removal without an impact on reactor water sulfate.

Iron Removal Filter Septa Design

Iron removal filter septa are defined as those septa capable of achieving 1.5 ppb or less effluent iron with non-precoated septa or with thin precoats (0.05 dry pounds/10" filter septum length) for precoated septa [2]. In BWR condensate service to date, only pleated media filter septa and hollow fiber filters (HFF) have been able to demonstrate the ability to meet the above definition for high efficiency iron removal septa. These septa can achieve low effluent iron concentrations without the use of precoats. In contrast, other septa media, such as yarn wound or melt blown, are unable to achieve low iron concentrations without precoat dosages greater than 0.05 dry pounds/10".

Pleated filter media include two basic types: upright pleats (offered by several suppliers) and layover pleats (offered by Pall Corporation). In both designs, the flow path is radial, from outside to inside. As the name implies, upright pleated septa have the pleats standing upright around an inner porous support core. In layover septa, the filter medium pleats are folded over each other, creating layers of pleats within the annular space between an outer protective layer and a center core.

In the past, both types of septa have been used in both precoat and non-precoat service. Currently, upright pleated septa are used in both precoat and non-precoat service, while layover pleated septa are used only in non-precoat service.

A variation of upright pleated septa consists of pleats surrounded by either wound yarn or melt blown polypropylene to provide a cylindrical surface that can be completely and evenly precoated to improve ion exchange performance while maintaining low effluent iron concentrations. Graver DualGuard™ I filters have polypropylene pleats surrounded by a polypropylene mesh support layer covered with wound yarn that serves as the precoat retention media. DualGuard™ II filters have a melt blown polypropylene precoat retention layer over polypropylene pleats; the protective cage is on the outside of the precoat retention layer.

DualGuard™ III filters, similar to DualGuard™ II filters, are manufactured with a stronger cage to address warping of the filters experienced during service cycles of 4+ years at Quad Cities.

A recently introduced product, the Pall Power Generation Hydro-Guard PFM filter, contains internal 4-micron layover pleated media surrounded by a melt blown precoat retention layer with a reverse gradient pore size (similar to Hydro-Guard CoLD-R). This product is being tested in full scale use at one BWR station.

Hollow fiber filters (HFFs) are commonly used in BWR condensate service in Japan, achieving useful module lives greater than ten years. Oyster Creek is the first U.S. BWR to retrofit an Organo HFF technology prefilter system in condensate service. The equipment was provided by Graver Water Systems. The filters consist of double open ended type modules of 1-mm diameter polysulfone hollow fibers with a 0.14- μ m particle retention rating. The condensate flows from outside to inside the fibers, with the filtered effluent collected in upper and lower plenums. The size of the hollow fiber pores varies radially, with the smaller pores on the outside surfaces.

Condensate Filter Septa/Module Usage

The types of filter septa or modules used in both precoat and non-precoat application are shown in Table 9-2.

In non-precoat application, all stations except Oyster Creek, with a hollow fiber filtration system, use pleated septa. Septa with a 4-micron particle retention rating are installed at the majority of stations that use upright pleated septa. The exceptions are Brunswick, which uses 1-micron septa from Graver, and Susquehanna, which uses 2-micron Pall upright pleated septa. Susquehanna has an inefficient backwash system and experience has shown that slightly longer septa lives are achieved with 2-micron septa compared to 4- or 10-micron septa. Layover pleated septa are used at Clinton, Hope Creek, Leibstadt, and Limerick. Clinton is the only station with prefilters to use more than one septa type in its vessels.

At stations with filter demineralizers, a wider variety of septa types is used. Yarn wound septa are used in all vessels at three stations (Cofrentes, Duane Arnold, and Ringhals 1). DualGuard I septa are used in all vessels at Columbia and Vermont Yankee, and DualGuard II or III septa are used in all vessels at Browns Ferry and Cooper. Hatch uses Pall upright pleated septa in all its vessels. A mixture of septa types is used at six stations: Fermi 2; Leibstadt (pleated septa are not precoated); Monticello; Mühleberg; Peach Bottom; and Quad Cities.

In recent years, stations with CF/Ds have replaced yarn wound septa with pleated, as shown in Figure 9-1. In 1995, 96% of CF/D vessels used yarn wound septa compared with 22% in 2008, with a corresponding increased in pleated septa usage from 4% in 1995 to 78% in 2008. (The “Other” category includes some types of melt blown septa that were used at a few stations and were ineffective in removing insoluble iron. Their use has been discontinued.) This trend is in part responsible for feedwater iron reduction at BWRs with CF/Ds.

Table 9-2
Condensate filter septa/modules in service at BWR stations

Manufacturer	Model	Type	Rating (μm) (Note 1)	Where Used w/Precoat	Where Used w/o Precoat
Beck	PP	Yarn Wound	n/a (yarn)	Leibstadt	
Graver	AFA	Upright Pleated	1		Brunswick
Graver	DualGuard I	Upright Pleats with Yarn Wound Precoat Layer	1	Mühleberg, Vermont Yankee	
Graver	DualGuard I	Upright Pleats with Yarn Wound Precoat Layer	5	Columbia	
Graver	DualGuard II	Upright Pleats with Melt Blown Precoat Layer	1	Cooper	
Graver	DualGuard II	Upright Pleats with Melt Blown Precoat Layer	5	Browns Ferry, Cooper	
Graver	DualGuard III	Upright Pleats with Melt Blown Precoat Layer	1	Browns Ferry, Monticello, Peach Bottom, Quad Cities	
Graver	DualGuard III	Upright Pleats with Melt Blown Precoat Layer	3	Browns Ferry	
Graver	DualGuard III	Upright Pleats with Melt Blown Precoat Layer	5	Browns Ferry, Monticello, Quad Cities	
Graver	FEPP-6	Yarn Wound	n/a (yarn)	Mühleberg	
Graver	W. Beck 1030	Yarn Wound	n/a (yarn)	Cofrentes	
Idreco		Yarn Wound	n/a (yarn)	Ringhals 1	
Organo	HFF	Hollow Fiber	0.14		Oyster Creek
Pall	BPF-4	Layover Pleated	1		Clinton

Table 9-2
Condensate filter septa/modules in service at BWR stations (continued)

Manufacturer	Model	Type	Rating (µm) (Note 1)	Where Used w/Precoat	Where Used w/o Precoat
Pall	BPF-5	Layover Pleated	1		Hope Creek, Leibstadt, Limerick
Pall	HGPFM	Layover Pleats with Melt Blown Precoat Layer	4	Fermi 2	
Pall	HGPPB	Upright Pleated	2		Susquehanna
Pall	HGPPB	Upright Pleated	4	Monticello (Note 2), Peach Bottom, Quad Cities	Dresden, Laguna Verde, LaSalle, Leibstadt, Nine Mile Point, Perry, River Bend, Santa Maria de Garoña
Pall	HGPPB	Upright Pleated	10	Fermi 2, Hatch, Peach Bottom	
Pall	Permi-L	Yarn Wound	n/a (yarn)	Duane Arnold	
Pall	Permi-L2	Yarn Wound	n/a (yarn)	Fermi 2	

Table 9-2 Notes

1. Ratings may be absolute or nominal.
2. Septa with reduced number of pleats used.

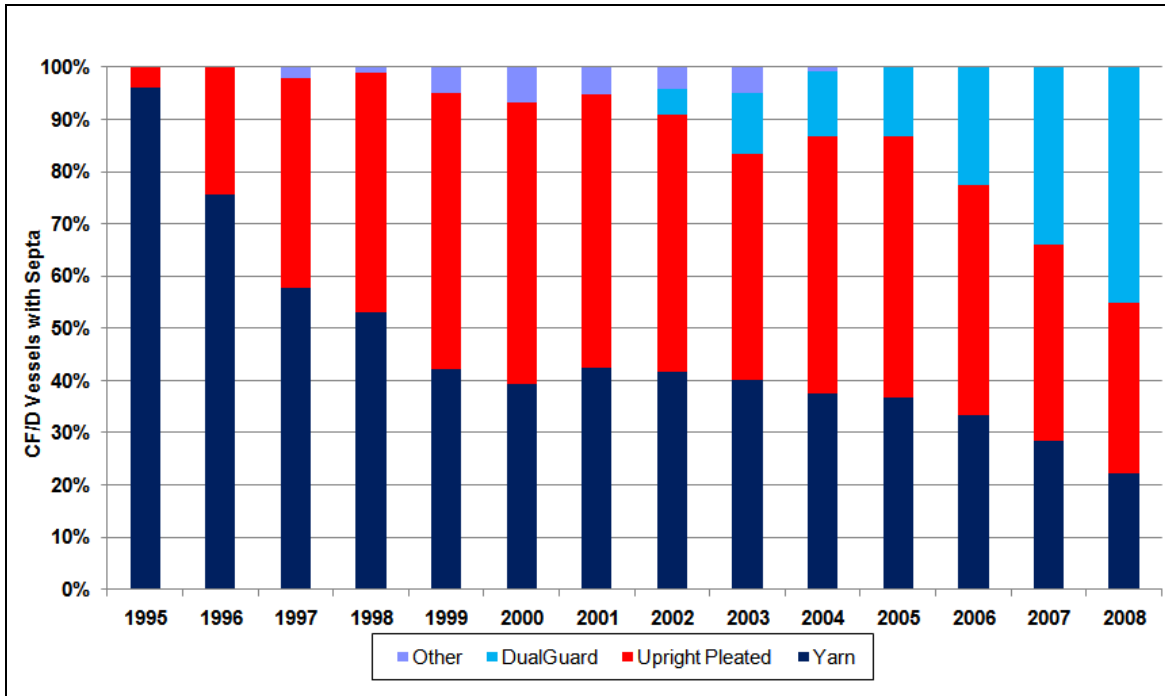


Figure 9-1
Septa usage among BWRs with CF/Ds [3]

Another contributing factor to lower feedwater iron is the use of septa with lower particle retention ratings. The rating can be absolute (i.e., 100% removal of all particles larger than the specified pore size) or nominal (depending on particle size distribution, some particles may pass through the filter media). The use of a precoat on yarn wound septa can effectively reduce the particle retention rating, since the purpose of the wound surface is mainly to support the precoat material and particles are mostly removed by the precoat layer.

The design may impact the iron removal performance of septa with similar particle retention ratings. For example, industry experience has shown that the iron removal efficiency of a Graver 5-micron DG II or III septum is approximately equivalent to that of a Pall 10-micron HGPPB septum, and that of 1-micron DG II or III septum is approximately equivalent to that of a Pall 4-micron HGPPB septum. In the Pall septum design, there are areas of the pleats that are not covered by precoat material, and thus are exposed directly to hotwell iron concentrations. In the DG II and III septa designs, the precoat and melt blown layers remove some of the larger iron particles, and the pleated medium is exposed to fluid with predominantly smaller particles. Therefore, a smaller pore size may be needed for DG septa to achieve the same iron removal performance of Pall HGPPB septa [3].

The trend towards lower particle retention ratings is illustrated in Figure 9-2, and average feedwater iron at BWRs with CF/Ds is shown in Figure 9-3.

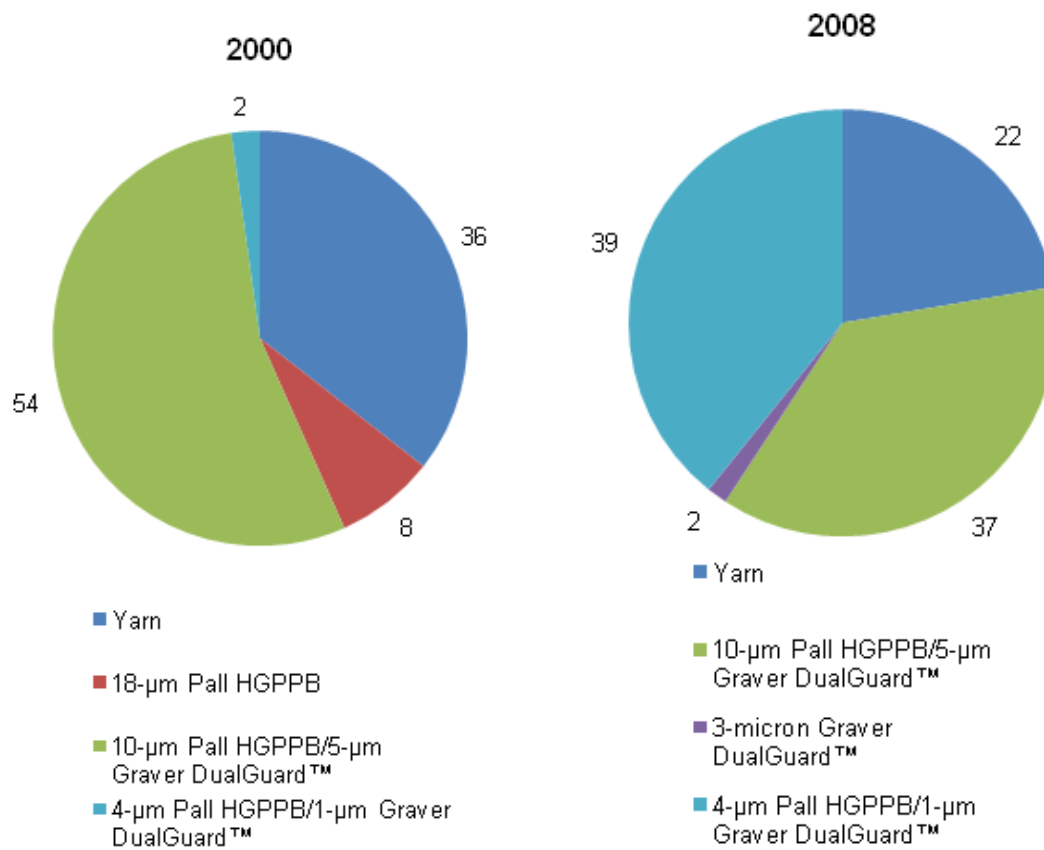


Figure 9-2
Particle retention ratings of CF/D septa (2000 and 2008) by number of vessels [6]

As shown in Figure 9-3, average annual feedwater iron at BWRs with CF/Ds has decreased by more than a factor of two since 2000. Contributing factors include decreased use of yarn wound septa and use of pleated septa with lower particle retention ratings.

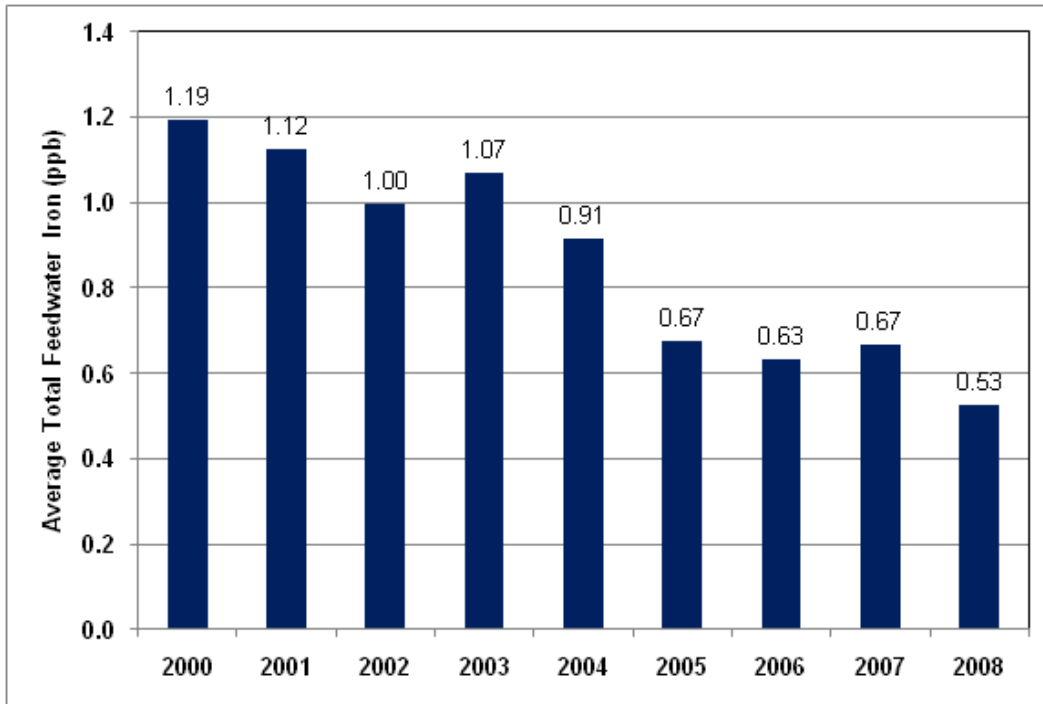


Figure 9-3
Average feedwater iron at BWRs with CF/Ds

Precoat Materials Usage in BWR CF/Ds

The types of precoat materials used in condensate filter demineralizers at stations that participate in the BWR Chemistry Monitoring and Assessment database are listed in Table 9-3. Most stations now use an all resin precoat, even on yarn wound septa. Browns Ferry and Hatch use a resin/fiber precoat in which 95% of the cation resin component is weakly acidic. This reduces the potential sulfate source term in the resin. In addition, Hatch has demonstrated longer run lengths to dP end point with this resin mixture, resulting in lower radwaste disposal costs. Cooper uses a resin/fiber premix as an underlay on its 5- μ m DualGuard II septa. Most stations are now using premixed resins rather than mixing separate anion and cation resins in the precoat tank. Columbia and Vermont Yankee both use cation resin rich premixes as overlays; Vermont Yankee also uses a body feed system to apply additional cation capacity to extend run lengths to effluent copper end point.

Table 9-3
Precoat materials used in BWR CF/Ds

Station	Type	Septa Type(s)	Comments
Browns Ferry	SAC/SBA WAC/SAC/SBA/fiber	DualGuard	Unit 1 Unit 2, 3
Cofrentes	SAC/SBA	Yarn	
Columbia	SAC/SBA	DualGuard	Cation resin overlay used for copper control
Cooper	SAC/SBA/fiber SAC/SBA	DualGuard	Resin/Fiber used as underlay on 5- μ m septa. All resin premix applied as overlay.
Cooper	SAC/SBA	DualGuard	Summer
Duane Arnold	SAC/SBA	Yarn	
Fermi	SAC/SBA	Yarn, Upright Pleated	
Hatch	WAC/SAC/SBA/fiber	Upright Pleated	
Leibstadt	SAC/SBA	Yarn	Premix normally used; separate components used as alternate
Monticello	SAC/SBA	DualGuard, Upright Pleated	
Mühleberg	SAC+SBA SAC/SBA	DualGuard, Yarn	Separate components normally used; premix used as alternate
Peach Bottom	SAC/SBA	DualGuard, Upright Pleated	
Quad Cities	SAC/SBA	DualGuard, Upright Pleated	
Ringhals 1	SAC/SBA	Yarn	
Vermont Yankee	SAC/SBA	DualGuard	Body feed used for increased cation capacity to extend run length

Table 9-3 Notes

SAC = strongly acidic cation

SBA = strongly basic anion

WAC = weakly acidic cation

/ indicates premix

+ indicates separate components mixed in precoat tank

An advantage of pleated septa use is that the precoat is used only for ion exchange and not for iron removal. For this reason, lower precoat dosages are commonly used on pleated septa compared to dosages used on yarn wound septa. Average precoat dosages are shown in Figure 9-4. For stations using different materials/dosages on different septa types, the values are weighted by number of vessels. For pleated septa without a precoat retention layer, the dry pounds per square foot value was calculated using a diameter equivalent to the outside diameter of the pleated surface. Duane Arnold, Cofrentes, and Fermi use septa that are less than two inches in diameter, which results in fairly low dosages per 10-inch septa length compared to the stations with larger diameter septa. Ringhals 1 and Mühleberg (KKM) use relatively high dosages on yarn wound septa. Columbia and Vermont Yankee, with copper alloy condenser tubes, use high precoat dosages for soluble copper removal.

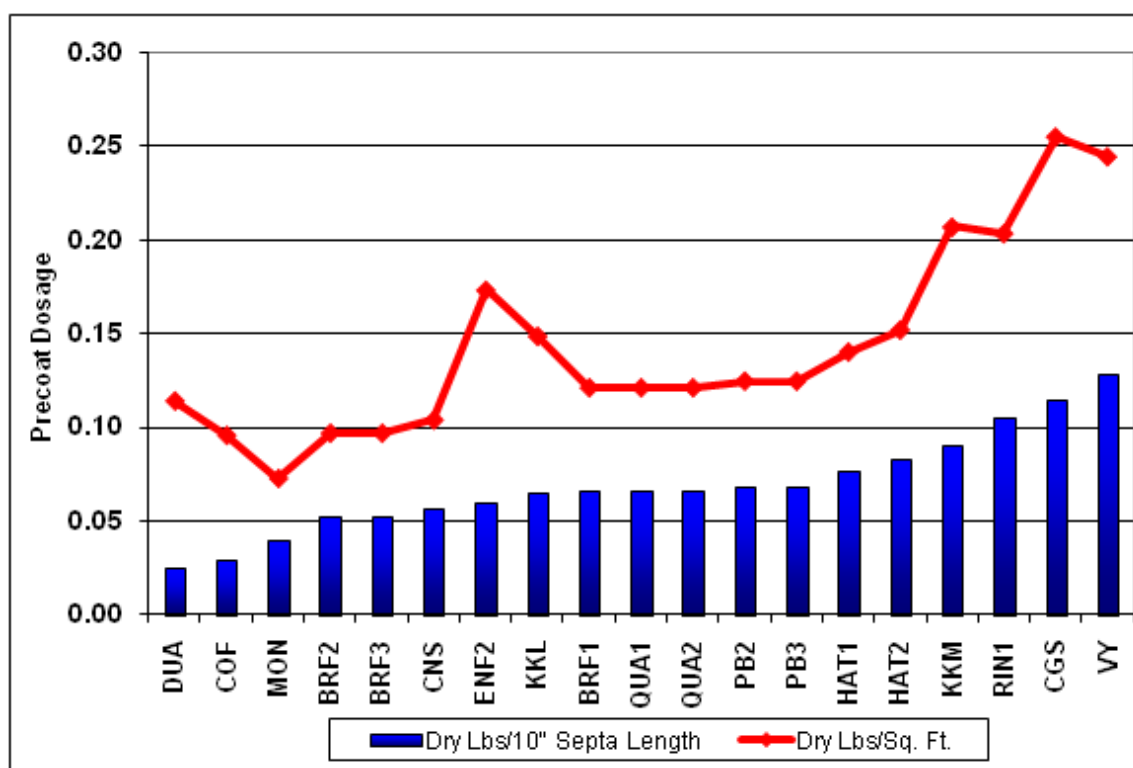


Figure 9-4
BWR CF/D average precoat dosage (weighted by number of vessels) – December 2008

As is the case with precoat dosage, there is a significant variation in the precoat strongly acidic cation exchange capacities among BWRs with CF/Ds, as shown in Figure 9-5. A high cation capacity is used at Columbia and Vermont Yankee for control of soluble copper. At Mühleberg, where a high precoat dosage is used, the cation capacity is high because of the lower cost of cation resin compared to anion resin. The low capacity at Browns Ferry and Hatch is the result of use of weakly acidic cation resin. Analysis of feedwater iron data in a previous report [3] found no general correlation between cation resin dosage and feedwater iron concentrations.

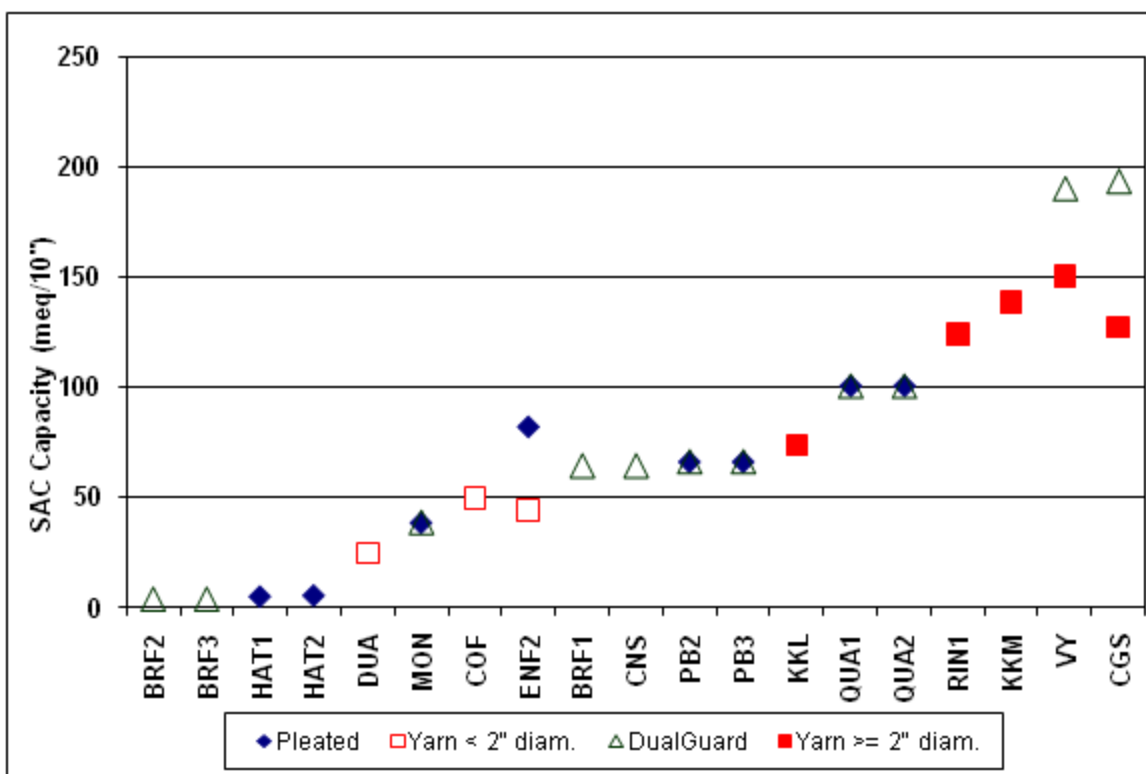


Figure 9-5
BWR CF/D average strongly acidic cation capacity per precoat (weighted by number of vessels) – December 2008

Impact of Septum Design on Ion Exchange Capability

Use of pleated media filter septa in condensate filter/demineralizer application first began in the mid-1990s. These septa are able to remove iron efficiently with much lower precoat dosages than are needed with yarn septa. However, ion exchange capability is a concern with some pleated septa designs, particularly since some areas of upright pleated septa are not covered by the thin precoats, allowing a percentage of the flow to pass untreated by ion exchange to the CF/D effluent. In comparison, yarn wound septa provide a continuous porous cylindrical surface upon which the precoat is deposited, allowing a more uniform precoat layer and better ion exchange capacity utilization.

A series of tests was conducted in 1996 by Memtec (now Pall Corporation) to compare the ion exchange performance of wound yarn and upright pleated septa. In the tests, a sodium chloride solution was passed through a single precoated septum. Influent and effluent conductivities were recorded and ionic leakage was calculated. The results indicated almost immediate ionic leakage with pleated septa and no leakage for yarn septa at up to 30% of utilized capacity [1].

Salt challenge testing was conducted by Graver Technologies in 2008 to evaluate the ion exchange performance of DualGuard I, II, and III septa compared with yarn wound septa. The conductivity results showed an immediate increase in ionic leakage for DualGuard II and III septa, indicating some flow areas with thin or no precoat deposition [3]. DualGuard I and wound yarn septa behaved similarly, having low initial ionic leakage which did not increase significantly below 40% utilization of the available capacity [3].

For CF/D plants where ion exchange is of particular importance (for example, plants with copper alloy condenser tubes or with a history of frequent condenser tube leaks), septa selection is a factor for maximizing ion exchange capability. Other factors that may affect ion exchange performance include: precoat quality; backwash effectiveness; flow distribution; and systems issues.

Reactor Water Sulfate Control in BWRs with CF/Ds

Plants with prefilters are able to operate their deep bed demineralizers with the ion exchange zone undisturbed by resin cleaning during the life of the bed, and reactor water sulfate control at these plants is discussed in Chapter 10. Although plants with CF/Ds have a lower quantity of cation resin in line with the condensate flow than plants with deep beds, and thus have a lower potential sulfate source in the cation resin component, they have faced challenges in controlling reactor water sulfate.

Prior to 2003, average reactor water sulfate at plants with CF/Ds was about the same or lower than that of plants with prefilters upstream of deep bed demineralizers, as shown in Figure 9-6. From 2003 – 2006, average reactor water sulfate at plants with CF/Ds was an average of about 50% higher than at plants with filters and deep beds. The contributing factors to higher sulfate at plants with CF/Ds include the following:

- Increased use of upright pleated septa without a precoat retention layer. These septa have been shown to contribute to elevated reactor water sulfate, especially when older septa are exposed to higher condensate temperatures during the summer months. The mechanism is thought to be age-related decomposition/desulfonation of cation resin trapped in the pleats. More information can be found in earlier reports [4, 7].
- Use of SureSeal attachment method at Browns Ferry. In 2002, Browns Ferry began using a septa attachment method in which the polypropylene septa end fittings were threaded directly onto the stainless steel tubesheet fittings. This resulted in numerous instances of septa detaching from the tubesheet fittings, resulting in cation resin leakage to the effluent side and reactor water sulfate excursions. In 2006, the station began installation of SealFast adapters on all CF/D vessels in Units 1, 2, and 3. Since installation of the new hardware, Browns Ferry has not experienced any incidents of detached septa, and average reactor water sulfate at the Browns Ferry units has decreased from greater than 2 ppb in 2005 to less than 1 ppb in 2008.

Increased use of DualGuard septa may be a contributing factor to lower reactor water sulfate at BWRs with CF/Ds, because the precoat retention layer prevents resin from becoming entrapped in the pleats. The relationship between condensate temperature and reactor water sulfate at Browns Ferry 2 is shown in Figure 9-7. In 2005, all vessels contained upright pleated septa. By the end of 2006, septa in four CF/D vessels had been replaced with DualGuard III septa. The conversion to DualGuard III was complete in April 2007. In 2008, although there is an increasing reactor water sulfate trend with increased condensate temperature, the magnitude of the increase is considerably less than in previous years when upright pleated septa without a precoat retention layer were used.

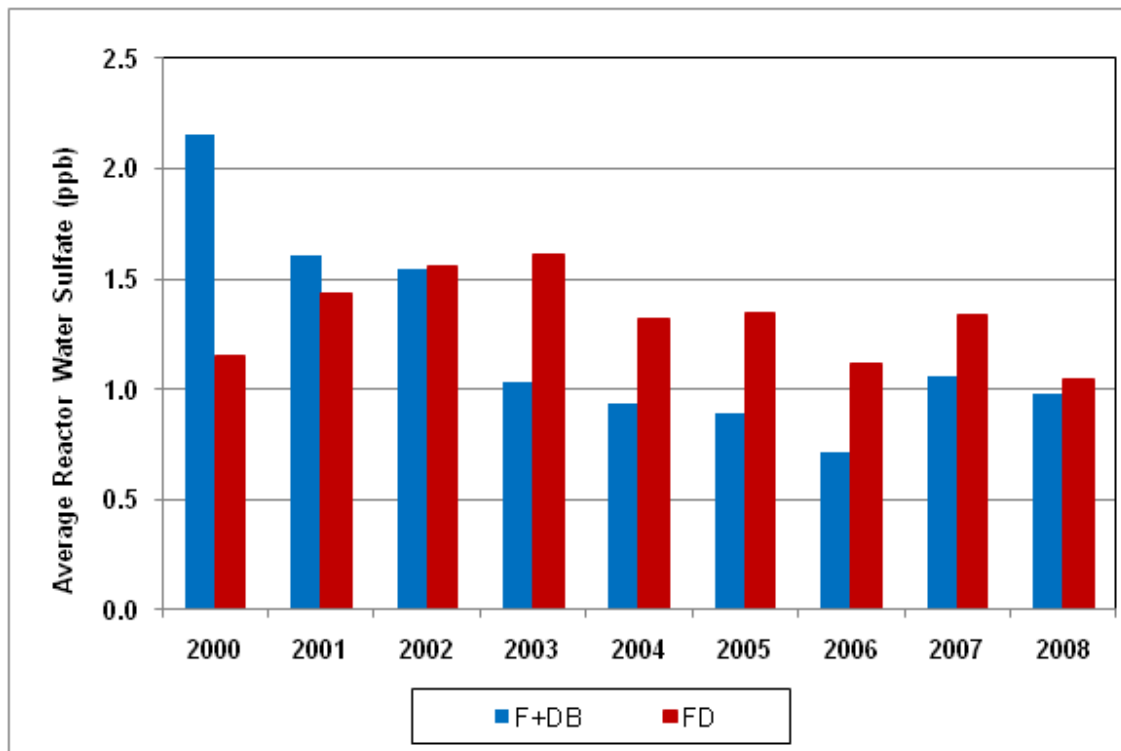


Figure 9-6
Average reactor water sulfate for plants with condensate filters

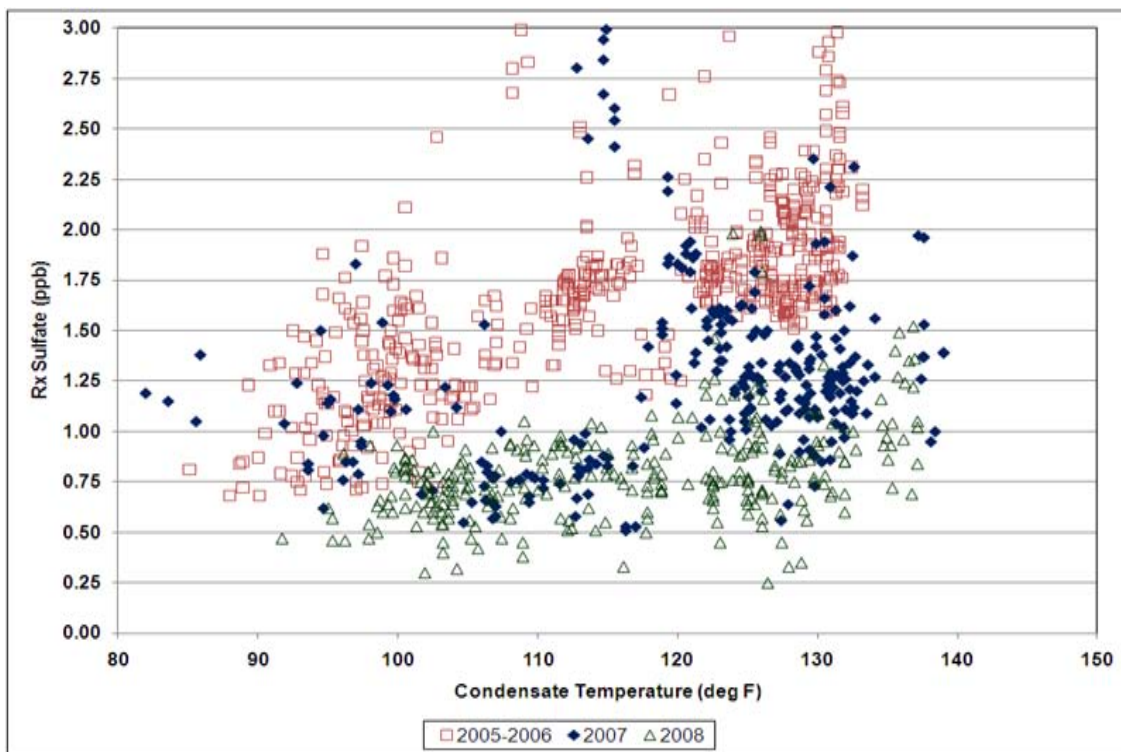


Figure 9-7
Browns Ferry 2 reactor water sulfate 2005 – 2008

Major Issues and their Current Status

With an increasing number of plants seeking license renewal for plant life extensions, along with increased challenges due to power uprates, condensate filter performance remains an important issue. The EPRI BWR Condensate Filter Users Group is involved in a continuing effort to evaluate filter system performance and disseminate information in order to address industry issues and drive the optimization of this technology. Specific issues for which updated information is available are discussed below.

Radwaste Issues

As BWRs with CF/Ds have installed higher efficiency iron removal septa and decreased precoat dosages, the quantity of iron relative to resin in the backwash water has increased. This has led to radwaste processing issues at some stations. Use of polyelectrolytes is a demonstrated method that has been implemented at several stations to improve the settling properties of solids in backwash wastes and the filterability of the liquid. Stations considering installation of septa with a lower particle retention rating should evaluate current liquid radwaste processing approaches and limitations and plan for improvements, such as polyelectrolyte injection, as appropriate. Polyelectrolyte injection is also used successfully at stations with prefilters to address iron settling issues in radwaste.

Ion Exchange Performance and Vessel Flow Distribution

Although pilot plant tests clearly indicated that the performance of precoat applied to pleated media was significantly inferior to that of precoat applied to yarn-wound septa, this has not been a major concern except at stations with medium to high cooling water total dissolved solids. The consequence of poor ion exchange capabilities is site specific, and depends on the frequency and size of condenser leaks, cooling water quality and the Reactor Water Cleanup flow rate. Where precoat performance is an issue, precoat materials selection may be altered when condenser leaks are encountered, or runs may be terminated early to minimize effects on reactor water chemistry.

Precoat uniformity has a direct effect on ion exchange performance, since areas containing no or very thin precoat result in condensate bypassing the ion exchange resin or early breakthrough, thus decreasing ionic removal capacity. This is also the case with thin precoat on pleated septa, since some of the filtration area of the pleats is not covered by precoat material. Precoat application methods can be optimized to enhance precoat uniformity by adhering to recommended precoat addition timing and concentrations.

Flow distribution patterns within a vessel may result in precoat erosion, for example, at the bottom of the septa in bottom tubesheet vessels.

Peach Bottom is installing Organo Integrated Flow Distributors (IFD) in all its bottom tubesheet vessels when septa are replaced to improve precoat uniformity. Although there is considerable experience in Japan in the use of IFDs with yarn wound septa, this was the first application with pleated septa and also the first U.S. experience. The results indicate that septa useful life has been increased, resulting in savings in radwaste and septa replacement costs. An additional benefit is reduced flow rates at the bottom of the vessel, resulting in lower forces on tubesheet fittings that have been subject to failure from IGSCC, aided by long term stress.

Vermont Yankee has made several system modifications, including installation of DualGuard I septa, IFDs, and SealFast hardware. The IFDs have resulted in more uniform precoats, and the reliable seal has allowed the use of cation rich precoat overlays for soluble copper removal, resulting in longer run lengths. The result has been a significant reduction in feedwater copper at Vermont Yankee, to concentrations as low as or lower than those prior to EPU [8].

Valve Issues

Precoat and backwash system valves and equipment are an integral part of the condensate filtration system and should be inspected at regular intervals to maintain optimum system performance. Air leakage can result in uneven precoating, resulting in shorter septa life and increased O&M and radwaste disposal costs. At stations with prefilters, valve integrity is important to optimize backwash efficiency, thus prolonging septa useful life.

At Fermi 2, pleated septa in one CF/D became prematurely fouled after a non-uniform precoat caused by air leakage to the precoat eductor. The fouling resulted in poor precoat distribution due to flow discrepancies, which led to increased reactor water chloride due to poor ion exchange performance [8]. The septa were replaced after less than three years in service.

Control System Issues

Several events related to condensate filtration control have occurred in recent years, some of which resulted in plant scrams. Events at River Bend, Browns Ferry 3, and Dresden 2 were described in a previous report [4].

Browns Ferry 3 initiated a manual scram in August 2009 due to a flow reduction in the reactor feedwater and condensate systems. A failure of the condensate filter demineralizer (CF/D) programmable logic controller (PLC) digital control system resulted in closure of five of nine CF/D outlet flow control valves, causing an approximately 50% reduction in condensate flow. A simultaneous failure of the CF/D system bypass to open automatically on increased system dP occurred, resulting in trips of two condensate booster pumps on low suction pressure. The initiating event was a fault in the output chassis of the 3H vessel control system, and a contributing cause was failure of the vessel outlet valves pneumatically operated lock-up valves to engage [9].

During PLC software /hardware maintenance, or when faults occur, the following strategies should be considered:

1. The system should be placed in a safe mode (e.g., disconnect air supply to valves so that they cannot change position).
2. Develop procedures in advance for PLC modifications.
3. Seek expert advice as appropriate.

During system installation or maintenance, when the bypass valve is being used to ensure feedwater flow, the valve should be locked open.

Power Uprate

Along with plant life extension, many BWRs have implemented or plan to implement power uprates. When planning a power uprate, the effects of increased flow and possibly increased inlet iron [7] must be addressed. The effects of increased flow and increased inlet iron are multiplicative; i.e., a 10% increase in flow combined with a 10% increase in inlet iron results in a 21% increase in filter iron loading.

Increased condensate flow results in:

- Higher area flow rates which affect filtration and ion exchange (in filter demineralizer plants)
- Higher filter dP resulting in shorter runs and shorter septa life and higher radwaste volumes
- Lower system dP margin may further limit useful septa life

Increased inlet iron results in:

- Higher dP resulting in shorter runs and higher radwaste volumes
- More solids to be processed in radwaste than would be expected by flow increase alone

Stations have addressed these issues in a variety of ways, including:

- Installation of an additional service vessel
- Increasing septa length and/or diameter
- Planned bypass flow during times when a vessel is out of service for backwashing

Summary

Through septa selection and system modifications, BWRs with condensate filters have reduced feedwater iron, feedwater copper, and reactor water sulfate concentrations, resulting in improved IGSCC mitigation and contributing to fuel reliability. Stations planning EPU should evaluate the impact on the condensate filter system and consider options to maintain good performance with increased EPU flow rate, temperature, and possibly hotwell iron concentrations. Stations with radwaste processing challenges that result from increased iron removal may benefit from polyelectrolyte addition to enhance radwaste settling. Ion exchange performance continues to be an issue for some CF/D stations; septa type and vessel flow distribution improvements are considerations for improved performance at these stations.

References

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2. *BWR Performance Monitoring*. EPRI, Palo Alto, CA: 2002. 1003600.
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10

DEEP BED CONDENSATE DEMINERALIZER EXPERIENCE UPDATE

Deep Bed Only Condensate Polishing

Chemistry Performance Summary

Since the 2007 update of the BWR Chemistry Performance Monitoring Report [1] was issued, four BWRs have added full flow condensate filtration upstream of their deep bed demineralizers. These are Dresden 2 and 3 (formerly with partial flow filtration), Oyster Creek, and Nine Mile Point 2. FitzPatrick, Grand Gulf, and Pilgrim are the three remaining deep bed only plants in the United States. There are no current plans at these three facilities to install condensate filtration, although at FitzPatrick, condensate filtration is likely to be installed if an extended power uprate is implemented. Grand Gulf is evaluating condensate filtration in conjunction with extended power uprate.

Annual average reactor coolant sulfate, reactor coolant chloride, feedwater iron, and feedwater copper (for those plants with copper alloy main condenser tubes) concentrations are shown in Figures 10-1 through 10-4, respectively, for plants with deep bed only (DB) condensate polishing for the years 2005-2008. With the exception of Grand Gulf, all deep bed only plants have been able to achieve annual sulfate medians < 2 ppb. Grand Gulf experienced elevated reactor coolant sulfate levels in 2007 primarily due to operation with older beds containing anion resin that was kinetically impaired. The station has historically operated with standard 10% cross-linked cation resin in an effort to improve feedwater iron control. All stations have been able to achieve an annual median reactor coolant chloride value < 1.0 ppb, with most values < 0.5 ppb.

Chinshan 1 and 2 and Kuosheng 1 reported median feedwater iron < 1.0 ppb in 2007 and 2008. Feedwater iron has been on an increasing trend at Grand Gulf and Pilgrim over the past four years. Pilgrim has experienced increased CDI iron concentrations over the past few years and has also experienced issues with resin cleaning system equipment. Increasing feedwater iron at Grand Gulf is related to the installation of multiple newer resin beds to address increasing sulfate concentrations. Reported feedwater iron concentrations at Grand Gulf are also impacted by sample system equipment issues.

Three of the DB plants have main condenser tubes constructed of copper alloys. In an effort to reduce feedwater copper, FitzPatrick increased the volume of cation resin in each condensate demineralizer from 90 ft³ to 105 ft³, while maintaining the same overall bed volume. Kuosheng 1 has reported median feedwater copper ≤ 0.05 ppb since 2006.

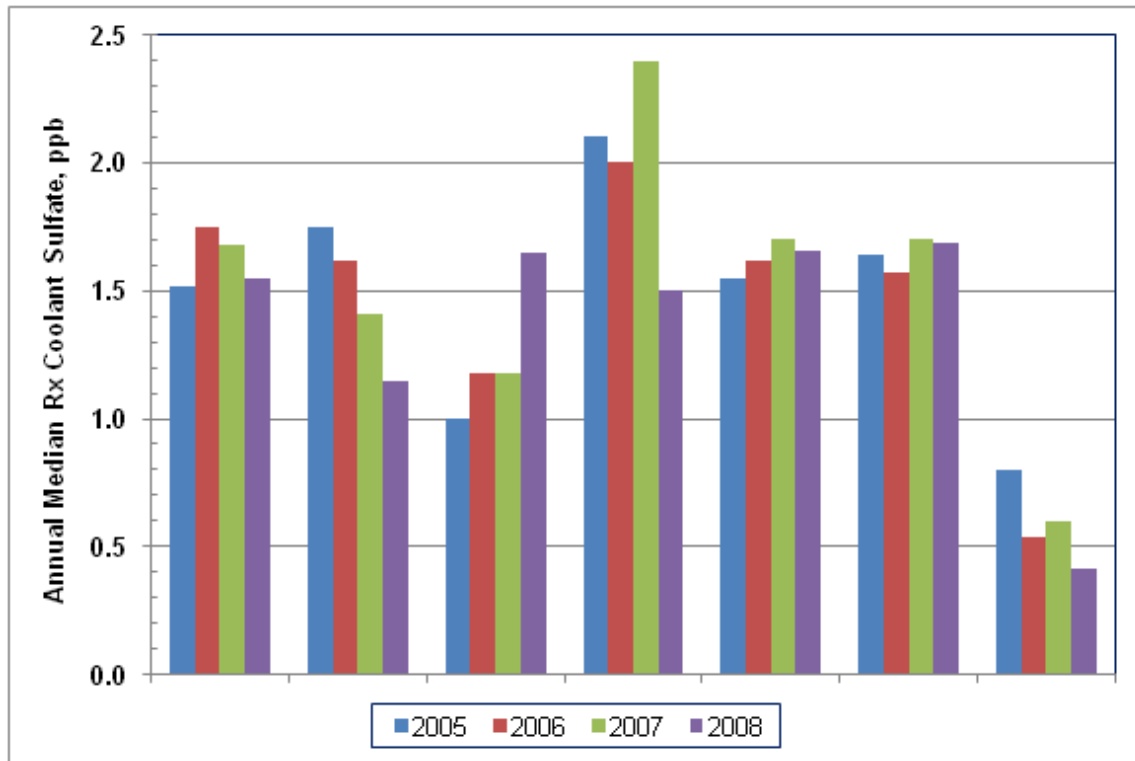


Figure 10-1
Median reactor coolant sulfate for 2005 – 2008 (deep bed only)



Figure 10-2
Median reactor coolant chloride for 2005 – 2008 (deep bed only)

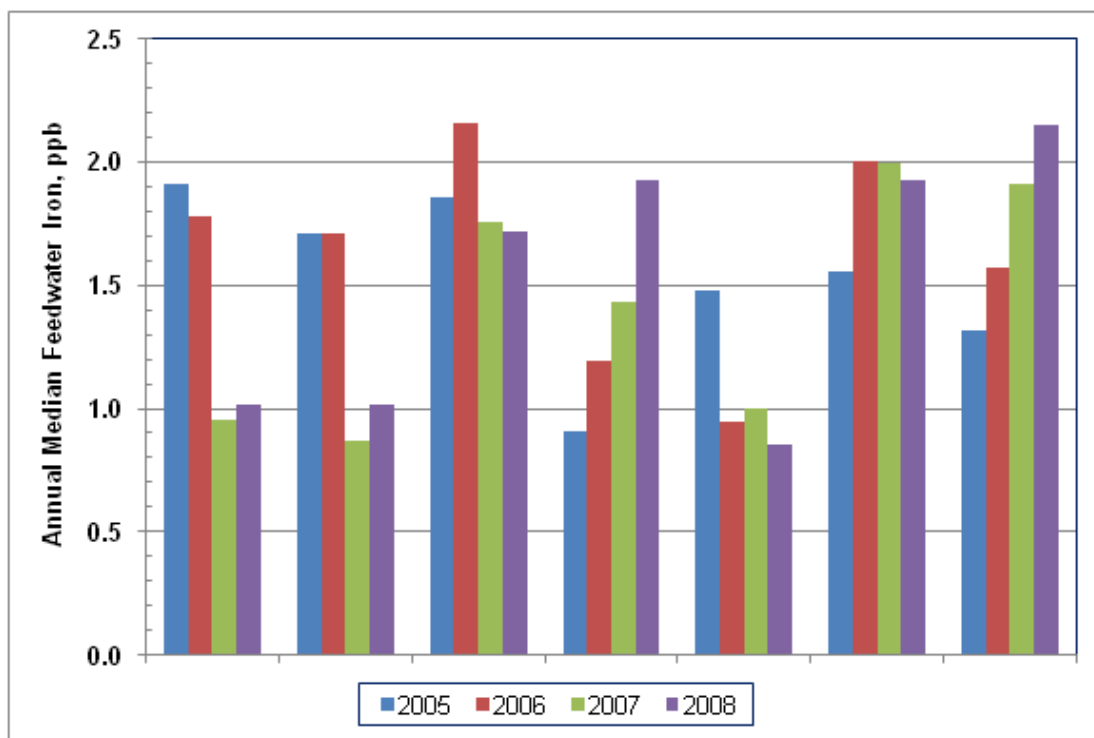


Figure 10-3
Median feedwater iron for 2005 – 2008 (deep bed only)

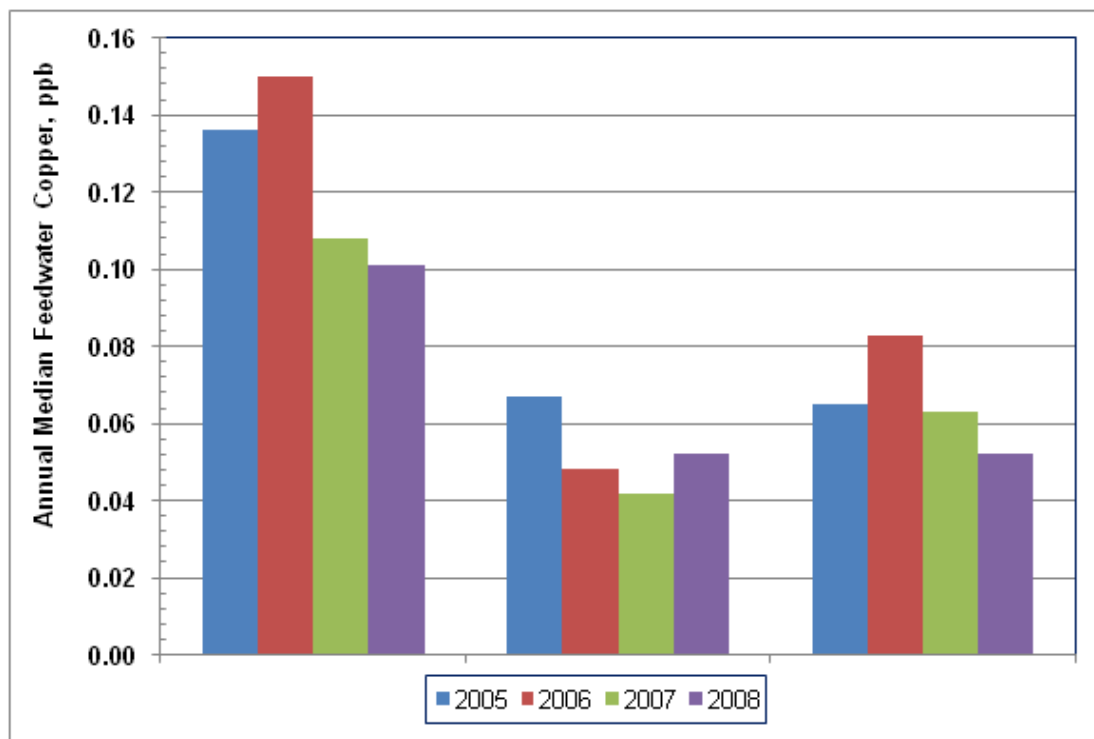


Figure 10-4
Annual average feedwater copper for 2005 – 2008 (deep bed only with copper alloy condenser tubes)

Resin Usage

Resin selection is one important variable influencing feedwater iron, copper, and reactor coolant sulfate control at Deep Bed Only plants. A listing of resins in use at these plants is presented in Table 10-1. The information in this table, along with additional details, is annually updated and distributed to the industry in the EPRI BWR Deep Bed Resins electronic report.

Table 10-1
Resins used with deep bed only condensate polishing

Plant	Supplier/ Manufacturer	Cation Resin (Supplier/Mfgr.)	Anion Resin (Supplier/ Mfgr.)	Number of Vessels
Chinshan 1	Thermax	Tulsion T-46	Tulsion A-33	8
Chinshan 2	Thermax	Tulsion T-46	Tulsion A-33	8
FitzPatrick	Siemens/ Rohm & Haas	IRN-99	IRN-78	8
Grand Gulf	Siemens/Dow	C-361 C/HGR-W2	A-284C/ SBR-C	8
Kuosheng 1	Thermax	Tulsion T-46	Tulsion A-33	6
Kuosheng 1	Thermax	Tulsion T-46	Tulsion A-33	6
Pilgrim	Siemens/Dow	575C	A-284C/ SBR-C	7

Two of the seven DB plants use only high (>10%) cross-linked uniform particle size gel cation resins. Higher cross-linking has been shown in laboratory tests to improve the cation resin resistance to oxidation, thereby decreasing the amount of extractable organic sulfur species that are imparted to the bulk liquid, which would lower reactor coolant sulfate levels from this source. Also, the volume capacity increases and selectivity for cationic impurities improves as the cross-linking increases. FitzPatrick is the only DB plant using Rohm & Haas IRN-99, which is a strongly acidic, 16% cross-linked, uniform particle size gel cation resin with a harmonic mean diameter of about 530 microns. Dow 575C is a strongly acidic, 12% cross-linked, uniform particle size gel cation resin with a harmonic mean diameter of about 550 microns. Dow HGR-W2 is a strongly acidic 10% cross-linked cation resin with a Gaussian particle size distribution and a harmonic mean diameter of about 790 microns. With the smaller resin size, the Dow 575C and IRN-99 resins provide additional cation resin surface area per unit bed volume, which is expected to provide some additional benefit in insoluble iron removal. Thermax Tulsion T-46 is an 8% cross-linked gel cation resin with Gaussian particle size distribution.

Anion resin products in use are strongly basic Type I gel resins with quaternary amine functionality. Rohm & Haas IRN-78 is a uniform particle size resin with a harmonic mean diameter of about 620 microns, while Dow SBR-C and Thermax Tulsion A-33 have a Gaussian particle size distribution.

To help decrease the potential for resin separation in the service vessel due to flow transients, some plants purchase resin products which have been further processed so that the anion and cation resins have similar hydraulic properties, such that they are more difficult to classify

hydraulically (“less separable”) than standard resin mixtures. The tendency to separate could result in a cation resin heel in the bottom of the demineralizer vessel, contributing higher sulfate input to the reactor water than if a mixture of cation and anion resins, or an anion underlay, were present.

Resin Ratios and Anion Underlays

Resin volumes, cation to anion volume ratios, and anion underlay volumes for the Deep Bed Only plants are shown in Table 10-2.

Table 10-2
Resin volumes and resin ratios used with deep bed only condensate polishing

Plant	Total Bed Volume (ft³)	Total Bed Cation to Anion Resin Volume Ratio	Anion Underlay Volume (ft³)	Anion Underlay % of Total Bed Volume
Chinshan 1	140	0.56	30	21
Chinshan 2	140	0.56	30	21
FitzPatrick	195	1.17	60	31
Grand Gulf	290	0.66	120	41
Kuosheng 1	300	1.00	0	0
Kuosheng 2	300	1.00	0	0
Pilgrim	220	0.83	70	32

All of the U.S. Deep Bed Only plants and the Chinshan units use an anion underlay. When properly implemented, this strategy assures that the last resin contacted by the condensate in the down-flow demineralizer is anion resin, which has the final opportunity to remove sulfur impurities from the condensate prior to entering the reactor feedwater.

FitzPatrick has increased the cation to anion resin volume ratio from its previous value of 0.86 to 1.17 in an effort to improve feedwater iron and copper control. EPRI studies have shown that insoluble iron oxide particles in BWR condensate iron are attracted to the cation resin [1]. Resin samples show that iron crud is tightly adhered to the surface of the cation resin, while crud particles are only loosely held on anion resins and can be easily removed by from the anion resin surface with rinsing or minor mechanical agitation. Increasing the quantity of cation resin per bed is a potential action to incrementally improve iron and copper removal, but the increased sulfate source term must also be considered. At FitzPatrick, since 2001 when the use of IRN-99 cation resin was first implemented, sulfate control has improved. The increase in reactor water chloride and sulfate at FitzPatrick in 2008 is attributed to chronic condenser tube leaks.

The iron control benefit of increased cation resin capacity was first demonstrated in full-scale plant application at Susquehanna. Prior to installing prefilters, different ratios of standard resins were applied at Susquehanna, and it was found that 2:1 C/A (by volume) beds provided better

iron removal than 1:1 C/A (by volume) beds, which provided better iron removal performance than equivalent mix beds. The increased cation resin surface area per bed with the higher C/A coincides with improved iron removal. The disadvantage of an increased C/A ratio is that more cation resin is available to contribute ionic sulfate (from thermal desulfonation) and organic sulfur (from resin oxidation), and thus may reduce bed useful life based on reactor water chemistry (particularly sulfate).

Filter + Deep Bed Condensate Polishing

Chemistry Performance Summary

Plants with Filter + Deep Bed (F+DB) condensate polishing rely on the upstream filters to remove insoluble metal oxides and other particulate impurities from the condensate. With upstream full-flow filtration, there is normally no need to externally clean the deep bed demineralizer resins. This allows the resin bed to remain fixed throughout its useful life, so the resin ion exchange capacity can be more fully utilized while maintaining higher effluent quality compared with beds that are mixed (disturbed) by periodic external resin cleaning. For the purpose of this summary, Clinton is considered a Filter + Deep Bed Plant, since six of the nine demineralizer vessels have in-line upstream filters and thus, require no resin cleaning. The remaining three beds at Clinton must be cleaned by URC. Although Ringhals 1 has installed deep bed demineralizers, they are only used in the event of a condenser tube leak, and therefore Ringhals 1 is not included as an F+DB plant in this report.

Annual median reactor coolant sulfate, reactor coolant chloride, feedwater iron, and feedwater copper (for those plants with copper-alloy main condenser tubes) concentrations are shown in Figures 10-5 through 10-8, respectively, for current Filter + Deep Bed plants for the years 2005-2008.

Three plants are shown to have annual median reactor water sulfate values > 2 ppb. Increased reactor water sulfate at Brunswick 2 during the past two years has been attributed to several factors, including degraded rubber linings in the resin regeneration tanks, condenser leaks, RWCU performance issues, and resin heels. Oyster Creek and Nine Mile Point 2 are plants that have recently implemented full flow condensate filtration. Full flow filtration was implemented at Oyster Creek in 2007 and sulfate has been on a decreasing trend since then, now that the deep bed ion resins are undisturbed by cleaning. A campaign to remove resin heels and replace aged rubber linings (>40 years old) in service vessels at Oyster Creek is planned to begin in 2010 and is expected to further reduce the sulfate source term. Full flow filtration has been in service at Nine Mile Point 2 for about one year. In the past three to four years, Nine Mile Point 2 experienced problems with resin heel removal and RWCU performance issues that impacted sulfate control.

As shown in Figure 10-6, all plants have achieved annual chloride medians ≤ 1.0 ppb, with the majority of values less than 0.5 ppb. In 2008, River Bend experienced elevated chloride levels attributed to organic solvents used to repair sections of rubber linings in a number of the condensate demineralizers. Residual chlorinated organic compounds from new anion resins have also been identified as sources. The annual median in many cases is the LLD value; at Laguna Verde and Nine Mile Point, the LLD is 0.5 ppb.

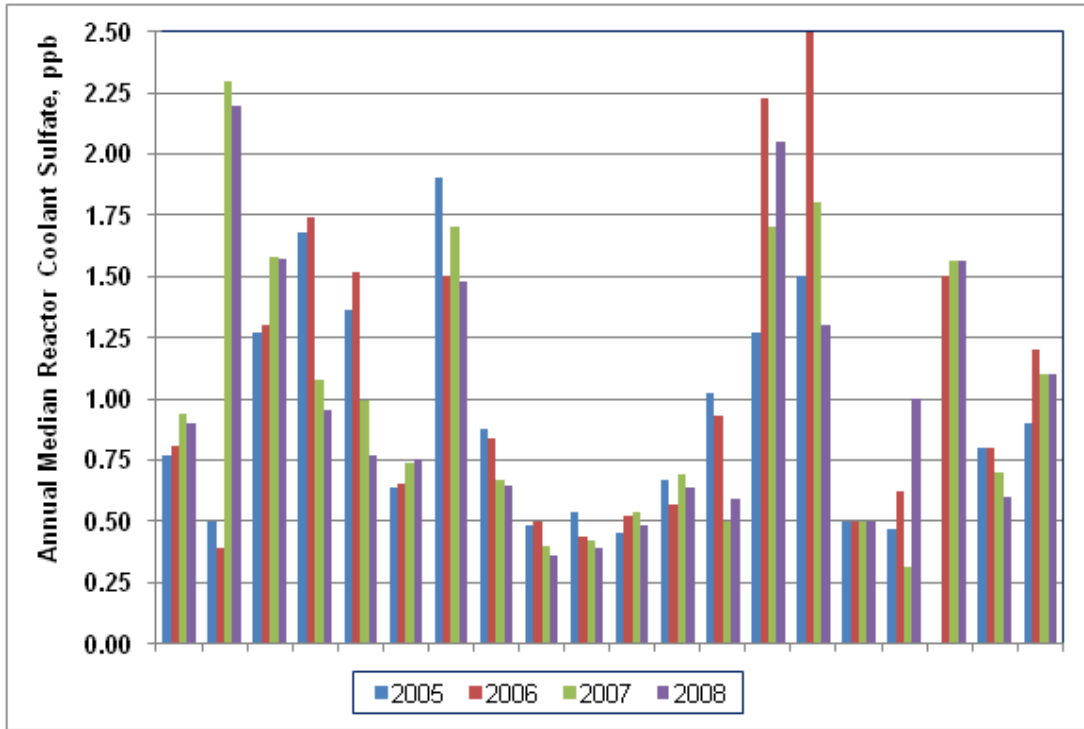


Figure 10-5
Annual median reactor coolant sulfate for 2005 – 2008 (filter + deep bed)

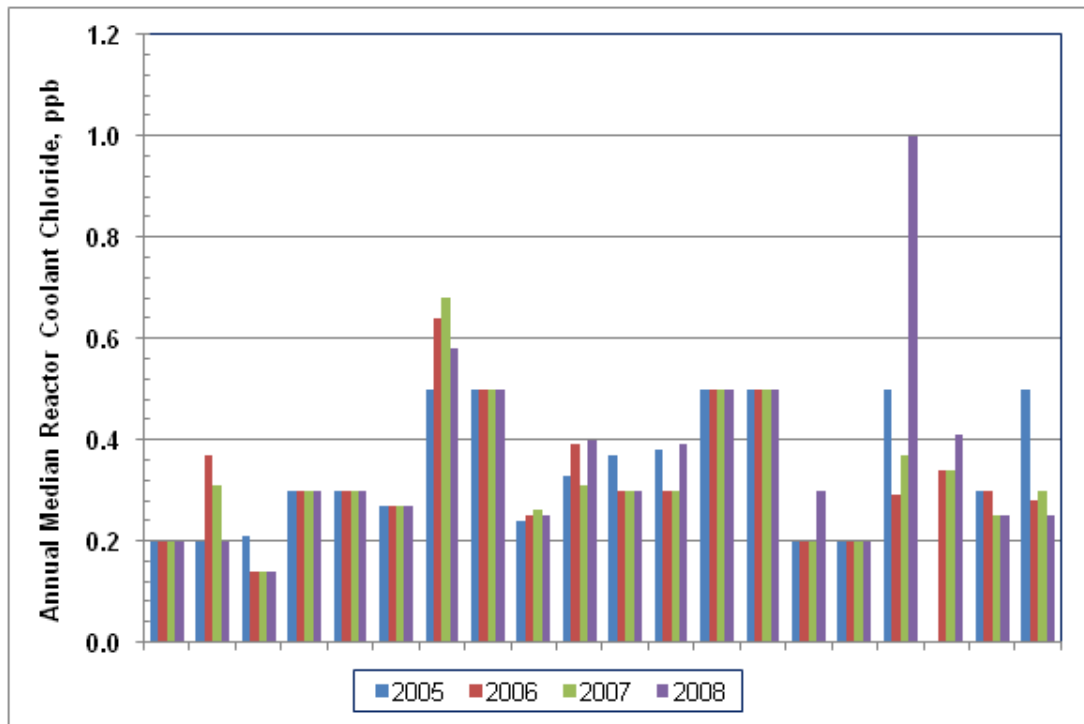


Figure 10-6
Annual median reactor coolant chloride for 2005 – 2008 (filter + deep bed)

In 2008, fourteen Filter + Deep Bed plants achieved median feedwater iron concentrations less than 0.5 ppb. Feedwater iron has consistently been less than 0.1 ppb at River Bend since filter operation began in 2002. Both Nine Mile Point units and Oyster Creek have observed a decrease in feedwater iron since filter operation commenced. Nine Mile Point 2 has an iron source in the pumped forward heater drains flow path which will prevent feedwater iron from decreasing to less than 0.1 ppb. LaSalle 1 observed a decrease in feedwater iron following the replacement of high pressure feedwater heaters. Median feedwater iron at Dresden 2 was very low in 2008, less than 0.02 ppb. Filters were not operational at Dresden 3 until late 2008 so the median value shown in Figure 10-7 reflects primarily operation as a deep bed only plant. Among plants with cascaded drains, Clinton, with partial flow filtration, is unable to achieve an annual median feedwater iron value less than 1 ppb. Hope Creek, Limerick 1 and 2 and Susquehanna 1 and 2 inject iron, which is the primary contributor to iron in the feedwater.

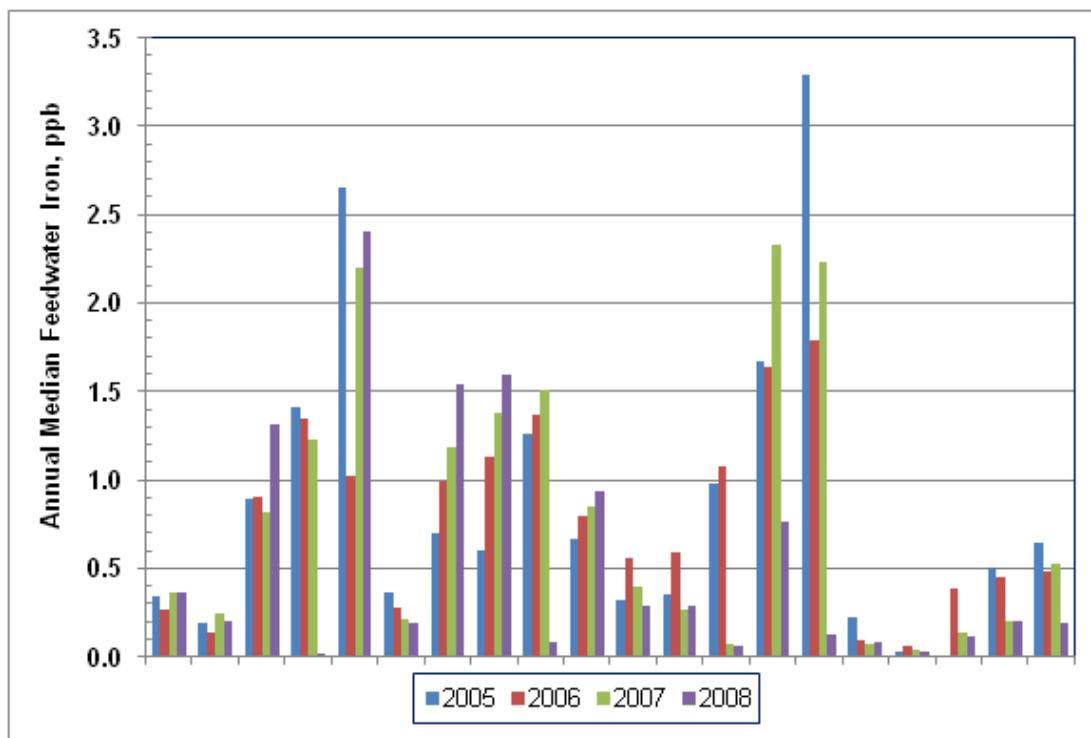


Figure 10-7
Annual median feedwater iron for 2005-2008 (filter + deep bed)

As shown in Figure 10-8, most Filter + Deep Bed plants have been able to achieve median feedwater copper concentrations less than 0.05 ppb. The 2008 values at both Nine Mile Point units are above 0.05 ppb and are higher than the other plants in this category. This is believed to be due to the analytical methods used at the station which results in a higher lower limit of detection (LLD). The copper alloy condenser tubes at Laguna Verde 1 and 2 were replaced with titanium tubes in their most recent refueling outages.

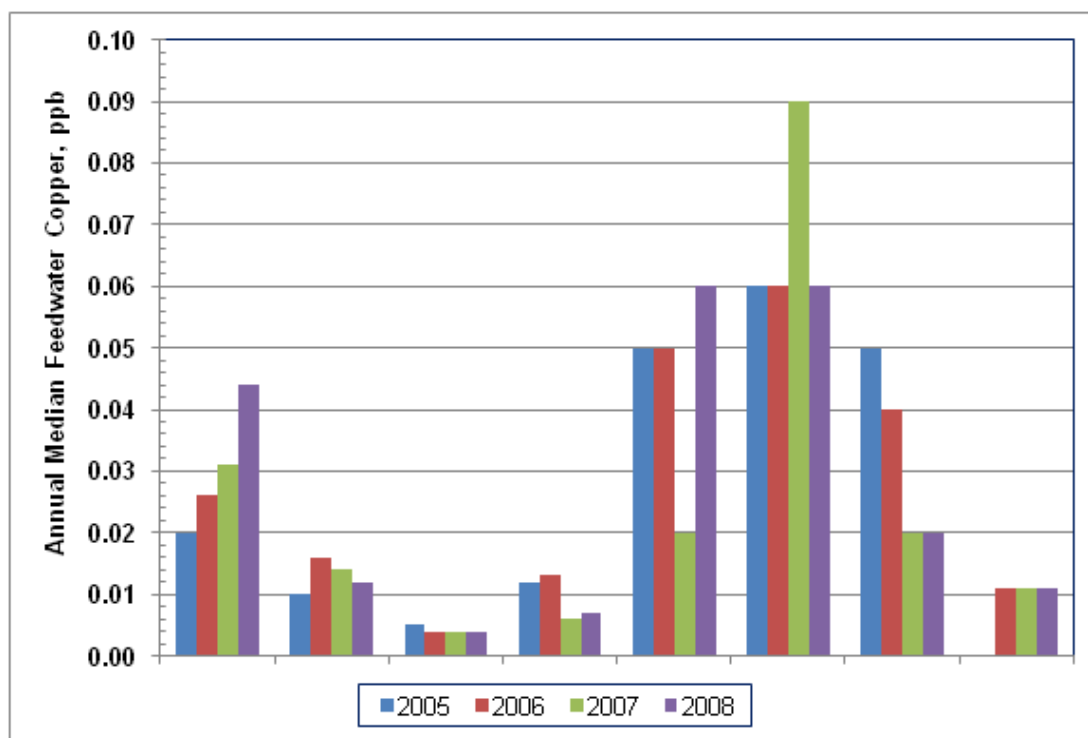


Figure 10-8
Annual median feedwater copper for 2005 – 2008 (filter + deep bed with copper alloy condenser tubes)

Resin Usage

The ion exchange resins used in deep bed demineralizers with upstream filters are listed in Table 10-3. The cation resins are all gel types having cross-linkage of 10% or higher. Macroporous cation resins are used at LaSalle 1 and Santa Maria de Garoña. At Clinton, six beds with upstream in-line filters used some weakly acidic cation (WAC) resin to reduce the sulfate source term from the oxidation and thermal desulfonation of standard (sulfonated styrene divinylbenzene) cation resins [Note: Prior to publication, the station reported that use of weakly acidic cation resin has been discontinued. Information on current resin usage was not provided.] The deep beds which are downstream of the prefilters are not periodically cleaned and the ion exchange zone in the mixed bed and anion underlay is not intentionally disturbed during the life of the beds. The remaining three beds use a standard 10% cross-linked cation resin. These beds do not have prefilters and the resins must be cleaned periodically, disturbing the ion exchange zone each time.

Two of the current twenty Filter + Deep Bed plants are not using high cross-linked cation resins. Sixteen plants are using high cross-linked resins exclusively. Many of the resins used are the same resins used by the DB plants and discussed earlier. Rohm & Haas IRN-97 is a 10% cross-linked macroporous cation resin with UPS distribution and IRC-86RF is a polyacrylic copolymer weakly acidic gel cation resin. Dow 545C is a 14% cross-linked gel cation resin with UPS

distribution. Rohm & Haas Amberlite 252 RF H is a 12% cross-linked macroporous cation resin and 9000 OH is a macroporous anion resin. At Santa Maria de Garoña, the anion resin is regenerated twice, about every 3.5 years, before it is replaced after about eleven years in service, resulting in reduced resin purchase and disposal costs.

Table 10-3
Resins used with filter + deep bed condensate polishing

Plant	Supplier/ Manufacturer	Cation Resin (Supplier/Mfgr.)	Anion Resin (Supplier/Mfgr.)	# of Vessels
Brunswick 1	Rohm & Haas	IRN-170 premix (IRN-99)	IRN-170 premix (IRN-78)	4
	Dow	545C	SBR-C	2
Brunswick 2	Rohm & Haas	IRN-170 premix (IRN-99)	IRN-170 premix (IRN-78)	6
Dresden 2	Siemens/Dow	545C	A284/SBR-C	8
Dresden 3	Siemens/Dow	575C	SBR-C	8
Clinton	Siemens/Dow	HGR-W2	SBR-C	3
	Siemens/Rohm & Haas	IRN-99/IRC-86RF (1)	IRN-78	6
Hope Creek	Rohm & Haas	IRN-99	IRN-78	7
Laguna Verde 1	Rohm & Haas	IRN-170 premix (IRN-99)	IRN-170 premix (IRN-78)	7
Laguna Verde 2	Rohm & Haas	IRN-170 premix (IRN-99)	IRN-170 premix (IRN-78)	7
LaSalle 1	Rohm & Haas	IRN-97/IRN-99 (2)	IRN-78	7
LaSalle 2	Rohm & Haas	IRN-99	IRN-78	7
Limerick 1	Siemens/Dow	NR-550-LS mixed bed/575C	NR-550-LS mixed bed/SBR-C Underlay: A-284-LS/SBR-C	8
Limerick 2	Siemens/Dow	NR-550-LS mixed bed/575C	NR-550-LS mixed bed/SBR-C Underlay: A-284-LS/SBR-C	8
Nine Mile Point 1	Siemens/Dow	575-C	SBR-C	6
Nine Mile Point 2	Siemens/Dow	575-C	SBR-C	9
Oyster Creek	Rohm & Haas	IRN-99	IRN-78	7
Perry	Rohm & Haas	IRN-97	IRN-78	6
River Bend	Siemens/Dow	C-361/HGR-W2	A-284C/SBR-C Underlay: A-284LS/SBR-C	10
Santa Maria de Garoña	Rohm & Haas	Amberlite 252RF H	Amberjet 9000 OH	6
Susquehanna 1	Siemens/Dow	C-471 SG/545C	A-284C/SBR-C Underlay: A-284LS/SBR-C	7
Susquehanna 2	Siemens/Dow	C-471 SG/545C	A-284C/SBR-C Underlay: A-284LS/SBR-C	7

Notes

1. Beds with upstream prefilters contain 28 ft3 of IRC-86RF in top layer, along with 42 ft3 of IRN-78. Middle layer contains 28 ft3 of IRN-99 and 35 ft3 of IRN-78. (This mixture has been discontinued; no weakly acidic cation resin is currently used).
2. Transitioning to IRN-99.

Resin Ratios and Anion Underlays

Nineteen of the twenty plants currently with Filter + Deep Bed condensate polishing report adding some anion resin as an anion underlay when a bed is replaced. As shown in Table 10-4, underlay volumes range from as low as 21 ft³ to as high as 75 ft³. By percentage of total bed volume, Nine Mile Point 1 has the largest underlay, while Perry has the smallest. As with Deep Bed Only plants, the use of anion underlay tends to provide better sulfate control, particularly during operating periods of peak condensate temperature. This practice also tends to extend the service period during which resin beds can maintain acceptable effluent sulfate, thus extending life of the resin bed.

Table 10-4
Resin volumes and resin ratios used with filter + deep bed condensate polishing

Plant	Total Bed Volume (ft ³)	Total Bed Cation to Anion Resin Volume Ratio	Anion Underlay Volume (ft ³)	Anion Underlay % of Total Bed Volume
Brunswick 1	180	0.32	40	22
Brunswick 2	180	0.32	40	22
Dresden 2	180	0.38	60	33
Dresden 3	180	0.50	60	33
Clinton	195	0.44	60	31
		0.40	56	29
Hope Creek	315	0.45	75	24
Laguna Verde 1	168	0.38	21	12.5
Laguna Verde 2	168	0.38	21	12.5
LaSalle 1	203	0.53	56	27
LaSalle 2	203	0.45	56	27
Limerick 1	320	0.57	30	9.3
Limerick 2	320	0.57	30	9.3
Nine Mile Point 1	170	0.62	60	36
Nine Mile Point 2	250	0.79	60	24
Oyster Creek	147	0.40	60	41
Perry	259	0.54	21	8.1
River Bend	145	0.61	30	21
Santa Maria de Garoña	140	1.0	0	0
Susquehanna 1	275	0.49	75	27
Susquehanna 2	275	0.49	75	27

Limerick 1 and 2, Susquehanna 1 and 2, and River Bend use an anion resin for the underlay that has a larger particle size than normal for the purpose of reducing the tendency for cation resin beads to migrate into the anion underlay during the service life. The main concern is that over time or due to flow and pressure transients, cation resin could migrate towards the bottom of the

vessel, thus decreasing the effectiveness of the anion underlay to minimize reactor water sulfate. This is less of a concern for Deep Bed Only plants as the anion underlays must be reestablished following each resin cleaning. The median sulfate values for the Filter + Deep Bed plants do not strongly support the hypothesis that resin separation during service is a widespread occurrence, as some plants not using larger particle size anion resins for the underlay have reactor water sulfate concentrations comparable to or lower than those of plants using the larger size anion resins. As the anion resin particle size increases, the surface area per unit bed volume decreases so the overall sulfate mass transfer rate will be lower. The use of anion resin with a larger mean particle size in the underlay may provide a level of assurance in maintaining or reducing sulfate, although the cost of these resins is likely to be higher. Plants that are more susceptible to flow disturbances that promote resin separation due to plant specific design and operating factors may benefit from this approach.

In the absence of significant condenser leaks, plants with Filter + Deep Bed condensate polishing achieve resin useful lives of three to four years. This results in significantly lower operating costs for resin purchase and disposal compared to Deep Bed Only plants, which typically replace resins after one to two years of service. Longer achievable useful resin life at Filter + Deep Bed plants is attributed to several factors, including:

- Ion exchange performance is optimized as the beds can operate undisturbed.
- The cation resins are not routinely subject to high oxygen conditions and crud loading that promotes oxidation, which would result in increasing the potential source term for organic sulfur products.
- Resin beds are not subject to resin losses from the cleaning process.

Other Factors Impacting Performance

The previous reports [1, 2, 3] include details on design and operational factors that impact the performance of deep bed only plants in the areas of feedwater iron and reactor coolant sulfate control. Discussion topics included condensate operating temperature, hotwell iron levels, vessel area flow rates, and resin cleaning frequency and performance. This information is not repeated here.

Maintenance of Condensate Polishers and Support Systems

The 2002 BWR Chemistry Monitoring Report [3] good practices for implementing an effective demineralizer system maintenance program include internal vessel inspections, isolation valve maintenance, and preventive maintenance of resin cleaning and transfer systems.

A number of plants have inspected condensate demineralizer and resin regeneration system vessel rubber linings and have found degraded conditions such as blistering, and, in some cases, missing sections of lining. Rubber lining material is known to degrade over time. The vulcanized natural rubber can become a sulfate source, and can physically obstruct flow and affect ion exchange performance if the adhesive system holding the rubber sheets to the vessel walls and other internal surfaces fails. As an alternate to replacing/repairing rubber linings with new rubber, several plants have removed the rubber lining and converted to a ceramic coating system.

Inspections have also found degraded vessel underdrain systems as well as inlet distributors. Some plants have inspected resin traps (located in the demineralizer effluent piping) and have found torn mesh screens and missing internal bolts. These findings support the need to perform periodic inspections and plan for repairs when flaws are found.

Going Forward

The remaining deep bed only plants will continue to struggle to achieve feedwater iron values of 0.1-1.0 ppb, recommended for chemistry optimization. Resin cleaning system upgrades can result in improved cleaning system reliability, incrementally lower feedwater iron and reduced liquid waste generation. However, feedwater iron will likely continue to remain above 1.0 ppb. Extended power uprate (EPU) is being considered for FitzPatrick and Grand Gulf. Full flow condensate filtration will likely be implemented at these plants should EPU be approved.

Implementation of extended power uprates (EPU) challenges condensate treatment system operations. For Filter + Deep Bed plants, where prefilters were installed as a plant retrofit, processing additional condensate flow as a result of EPU may not be possible with the current available condensate system differential pressure margin. Brunswick was able to add additional margin for EPU operation by increasing the septa length. Susquehanna 1 and 2 and Laguna Verde 1 and 2 have installed or are planning to install additional deep bed demineralizers and condensate filters for EPU.

In addition, full power operation under EPU conditions also results in increasing condensate temperatures. Plant heat balances typically show that operating temperatures at the inlet to the condensate treatment system under EPU conditions can increase between 5 and 8°F. Higher average condensate temperatures and higher peaks in the summer months along with higher superficial velocity through the beds increase the challenge to control reactor water sulfate as the cation resin decomposes at a faster rate. EPU evaluations should consider the impact on achieving the long term chemistry optimization goals defined in the 2008 Revision of the BWR Water Chemistry Guidelines [4]. Plants should consider rubber lining repair/replacement and demineralizer internal hardware upgrades as part of EPU and license extension activities.

With the implementation of the INPO Chemistry Effectiveness Indicator (CEI), all plants are more cognizant of condenser leak status, as the CEI increases if reactor coolant chloride levels exceed 1.0 ppb. As a result, it is important that condenser leakage be routinely monitored and the ionic loading of the deep bed demineralizer resin tracked to ensure that increases in leak rate will not result in reactor coolant exceeding 1.0 ppb. Chloride and sodium will be the first ions to increase in the demineralizer effluent due to equilibrium leakage. Sulfate may also increase, even at low anion exchange resin loading, due to impaired sulfate kinetics. Plants with chronic condenser cooling water inleakage will have to detect, identify and plug leaks, and replace resins that have accumulated significant ionic loading from such leaks, to minimize CEI.

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11

SUMMARY OF REACTOR WATER CLEANUP DESIGN AND EXPERIENCE

Introduction

The 2007 update of the Boiling Water Reactor Chemistry Performance Monitoring report [1] introduced a new chapter on reactor water cleanup system design and experience. This chapter was added because of increased industry focus on optimizing reactor coolant chemistry control for IGSCC mitigation, radiation field control and fuel reliability. This section provides an update on RWCU experience, issues, and challenges.

In 2009, EPRI formed an RWCU Chemistry Users Group with the specific focus on industry issues related to improving chemistry performance and reliability of the RWCU system treatment equipment. The group will be rolled into the existing Condensate Filter Users Group to assist plants in meeting BWR water chemistry goals.

RWCU Design Overview

In the BWR RWCU system, a portion of the primary coolant is removed, cooled to allow impurity removal via ion exchange, reheated, and returned to the primary system. The major components of the RWCU system include: circulating pumps; heat exchangers; and demineralizers. The demineralizers may be filter/demineralizers and/or deep bed demineralizers. RWCU capacity is indicated as a percentage of rated feedwater flow.

The current operating BWR 2 designs (Nine Mile Point 1 and Oyster Creek) and the first of the BWR 3 designs (Dresden 2 and 3) have RWCU systems that are rated between 2% and 5% of total feedwater flow. The remaining BWR 3 designs as well as the BWR 4 through BWR 6 designs have RWCU systems that were originally sized for approximately 1% of total feedwater flow.

In most of the original designs, primary coolant is drawn from the reactor recirculation system and from the reactor vessel bottom head drain connection (to prevent stratification). In some designs, coolant is drawn from both recirculation loops, while in other designs coolant is drawn from only one recirculation loop. Inside primary containment, piping from the vessel bottom head drain connection ties into piping from the recirculation system connection(s) to form a common header. There is an inboard containment isolation valve before the line exits primary containment. Outside of primary containment, coolant first passes through the outboard containment isolation valve before entering the suction of the RWCU pumps. The original designs included two circulating pumps. In most designs, each pump was sized to provide

50% of the rated RWCU flow capacity. The common RWCU pump outlet header is then routed through a series of heat exchangers referred to as the Regenerative Heat Exchangers (RHX). The typical design includes three RHXs arranged in series. Reactor coolant from the RWCU pumps flows on the tube side, while treated coolant from the treatment equipment outlet flows on the shell side. Temperature of the coolant leaving the tube side is reduced from reactor operating temperatures (~ 530°F) to approximately 230°F. The temperature of the coolant leaving the RHX is further reduced ($\leq 120^\circ\text{F}$) via a second series of heat exchangers referred to as the Non-Regenerative Heat Exchangers (NRHXs). Typical designs include two NRHXs in series. Reactor coolant passes through the tube side while closed cooling water passes through the shell side. Following the NRHXs, flow is then directed to the RWCU treatment equipment. The treatment equipment effluent is routed to the shell side of the RHXs where it is heated to $> 400^\circ\text{F}$ and returned to the primary system via the feedwater system. The connection to feedwater is typically just upstream of the feedwater piping containment penetration. The treatment equipment is designed to operate at reactor operating pressures.

Dresden 2 and 3, Nine Mile Point 1, and Oyster Creek, were designed with the main RWCU circulating pumps downstream of the treatment equipment (but prior to the RHX). Further, the treatment equipment at these plants is designed to operate at pressures of about 90-120 psig. This is accomplished through pressure control valves. One advantage at these plants is that the pumps operate at ambient temperature, which extends seal life. Another advantage is that dose rates and contamination levels on the pumps are low, resulting in low cumulative radiation exposure during pump maintenance compared with pumps located upstream of the heat exchangers and treatment equipment.

Some plants have modified the original piping design to locate the RWCU pumps between the NRHX and the treatment equipment. This was done to reduce pump seal problems. Pump location downstream of the NRHX is referred to as the “cold leg” location. The original design location is referred to as the “hot leg” location.

The two BWR 2 plants (Nine Mile Point 1 and Oyster Creek) and three of the early BWR 3 plants (Dresden 2 and 3 and Santa Maria de Garoña) were designed with both filter demineralizers and deep bed demineralizers in the RWCU system. Nine Mile Point 1 has two 100% capacity parallel trains, each with a filter demineralizer followed by a deep bed demineralizer. Oyster Creek has two 100% capacity filter demineralizers upstream of one common deep bed demineralizer. Each of the Dresden units contains three 100% capacity deep bed demineralizers; the original filter demineralizers at the Dresden units were not commissioned. The original design concept at the plants with both filter demineralizers and deep bed demineralizers was to precoat the filters with inert materials for particulate removal, with the deep beds performing ion exchange duty. Nine Mile Point 1 and Oyster Creek have since upgraded their septa and precoat the filters with premixed anion and cation resins for enhanced ion exchange.

The piping design allows for bypassing the treatment equipment and routing the effluent in a blowdown (letdown) lineup, either to the hotwell or radwaste, normally used for reactor level control during initial plant heatup.

A summary of key RWCU design parameters is provided in Table 11-1. As shown, eight plants that have performed power uprates are currently operating with RWCU capacity less than 1% of rated feedwater flow.

Table 11-1
BWR RWCU design summary

Plant	RWCU Capacity (% of Feedwater Flow, Normal/Maximum)	Treatment Type	Number of Vessels	Pump Location
Browns Ferry 1	0.9/1.15 (1)	F/D	2	Cold leg
Browns Ferry 2	0.9/1.15 (1)	F/D	2	Cold leg
Browns Ferry 3	0.9/1.15 (1)	F/D	2	Cold leg
Brunswick 1	0.85/0.85 (2)	F/D	2	Cold leg
Brunswick 2	0.85/0.85 (2)	F/D	2	Cold leg
Chinshan 1	1.3/1.3	F/D	2	Cold leg
Chinshan 2	1.3/1.3	F/D	2	Cold leg
Clinton	0.9/0.9 (2)	F/D	2	
Cofrentes	0.92/1.1	F/D	2	
Columbia	1/1	F/D	2	Hot leg
Cooper	1/1	F/D	2	Hot leg
Dresden 2	2.7/3.1	DB	3	Cold leg downstream of deep beds
Dresden 3	2.7/3.1	DB	3	Cold leg downstream of deep beds
Duane Arnold	1/1	F/D	2	
Fermi	1/1.1	F/D	2	Hot leg
FitzPatrick	0.91/1.1	F/D	2	Hot leg
Grand Gulf	1/1	F/D	2	Hot leg
Hatch 1	1/1	F/D	2	
Hatch 2	1/1	F/D	2	
Hope Creek	1/1	F/D	2	Hot leg
Kuosheng 1	1/1	F/D	2	Hot leg
Kuosheng 2	1/1	F/D	2	Hot leg
Laguna Verde 1	0.95/0.95	F/D	2	Hot leg
Laguna Verde 2	0.95/0.95	F/D	2	Hot leg
LaSalle 1	0.9/0.9 (2)	F/D	3	
LaSalle 2	0.9/0.9 (2)	F/D	3	
Leibstadt	1	F/D	2	
Limerick 1	1.1/1.1	F/D	2	Hot leg
Limerick 2	1.1/1.1	F/D	2	Hot leg
Monticello	1/1	F/D	2	Hot leg
Mühleberg	1/1.1	F/D	2	

Table 11-1
BWR RWCU design summary (continued)

Plant	RWCU Capacity (% of Feedwater Flow, Normal/Maximum)	Treatment Type	Number of Vessels	Pump Location
Nine Mile Point 1	2.7/5.1	F/D + DB	2 each	Cold leg downstream of deep beds
Nine Mile Point 2	1.75/2	F/D	4	Hot leg
Oyster Creek	2.6/4.6	F/D + DB	2-F/Ds; 1-DB	Cold leg downstream of deep beds
Peach Bottom 2	1.07/1.2	F/D	2	Hot leg
Peach Bottom 3	1.07/1.2	F/D	2	Hot leg
Perry	1/1	F/D	2	Hot leg
Pilgrim	1/1.5	F/D	2	Hot leg
Quad Cities 1	1.74/2	F/D	2	
Quad Cities 2	1.74/2	F/D	2	
Ringhals 1	2/4	DB	3	
River Bend	1/1	F/D	2	
Santa Maria de Garoña	2.33/6.7	F/D + DB	2 trains	Cold leg downstream of deep beds
Susquehanna 1	0.94/0.94 (2)	F/D	2	Hot leg
Susquehanna 2	0.94/0.94 (2)	F/D	2	Hot leg
Vermont Yankee	0.8/0.8 (2)	F/D	2	

Table 11-1 Notes

1. Flow increased for EPU
2. After EPU

RWCU Treatment Equipment

Filter/Demineralizers

Plants with RWCU F/Ds have one of two designs: a top tubesheet design where the septa are inserted through holes in the tubesheet and sealed with compression o-rings or metal welds; and a bottom tubesheet design where the septa are attached with adapters to the bottom tubesheet fittings.

In the top tubesheet design, flow enters the F/D vessel near the bottom and passes upward through the vessel, through the precoat material (which is on the outside surface of the septa) to the interior of the filter septa to the vessel top dome, and exits the vessel at a connection above the tubesheet. The precoat systems used for the top tubesheet plants are a two-tank design. The backwash method employed for the top tubesheet RWCU F/Ds is the air bump backwash which is described in detail elsewhere [2, 3]. The majority of the top tubesheet designs were provided by Delaval. The top tubesheet systems for the later BWR designs (BWR 5 and BWR 6) were provided by General Electric.

In the bottom tubesheet designs originally provided by Graver, flow enters the vessel at the bottom center, below the tubesheet. A pipe is connected from the entrance nozzle and passes through the tubesheet. The center pipe separates the inlet flow from the treated exit flow. Above the tubesheet, inlet flow from the center pipe is deflected radially outward via a baffle plate. Flow passes through the precoated septa and exits the vessel at the bottom, below the tubesheet. A single tank precoat system that includes a precoat tank and pump is provided with the Graver bottom tubesheet design. The backwash method employed for the bottom tubesheet RWCU F/Ds is the steady state Mod III backwash which is described in detail elsewhere [2, 3].

Plants having each basic RWCU F/D design are listed below:

- Top Tubesheet – Brunswick, Clinton, Cooper, Duane Arnold, FitzPatrick, Grand Gulf, Kuosheng, Monticello, Nine Mile Point, Oyster Creek, Perry, Pilgrim, River Bend, Quad Cities
- Bottom Tubesheet – Browns Ferry, Chinshan, Columbia, Hatch, Hope Creek, Leibstadt, Laguna Verde, LaSalle, Limerick, Mühleberg, Peach Bottom, Susquehanna, Vermont Yankee

Precoat materials used for RWCU F/Ds are similar to materials used for condensate F/Ds. Most plants still use a resin + fiber material. A number of the plants that have installed the high integrity septa are using all resin premixes. One example of an all resin premix not used in condensate but used on RWCU F/Ds at some plants with the high integrity septa is Epicor PD-23H. This mixture is anion resin enriched (two parts cation resin to three parts anion resin, per dry pound). No plants are known to be using a weakly acid cation resin precoat on RWCU F/Ds. Typical precoat loadings range from 0.2-0.62 dry lbs/ft² of filter area.

Deep Bed Demineralizers

The deep bed demineralizer designs at Nine Mile Point 1, Oyster Creek, and Dresden 2 and 3 are similar. All four of these plants were designed with condensate deep bed demineralizers, as well. The major difference between the RWCU deep bed demineralizers and the condensate deep bed demineralizers is the material of construction. The condensate deep bed demineralizers are rubber-lined carbon steel vessels, while the RWCU deep bed demineralizers are stainless steel vessels. Stainless steel vessels were provided in RWCU to eliminate the concern of rubber lining degradation, if, for example, high temperature water were inadvertently passed through the demineralizer vessel. Demineralizer internals (underdrain piping, inlet distributor piping) are also fabricated from stainless steel. The RWCU system at Ringhals 1 includes three deep bed demineralizers.

Resins for the RWCU deep bed demineralizers are prepared using the condensate demineralizer resin regeneration system equipment (Cation, Anion, and Mix and Hold Tanks). The RWCU deep beds were designed to hold a similar volume of resin as the condensate deep bed demineralizers to facilitate the use of the condensate demineralizer resin regeneration equipment. Like condensate demineralizer resins, RWCU deep bed resins are not regenerated. The goal at Oyster Creek and Nine Mile Point 1, since they have operable upstream F/Ds, is to operate the same deep bed for an entire fuel cycle before disposal. RWCU deep bed resins are typically not cleaned with the possible exception of preparation for disposal.

Deep Bed Resins

The resins used in the RWCU deep beds have historically been the same resins used in the condensate demineralizers at each of the RWCU deep bed plants. All four U.S. plants now use a high (>10%) crosslinked cation resin in the RWCU F/Ds (laboratory tests indicate that high crosslinked cation resins are more resistive to oxidation, and thus will have lower releases of sulfonated decomposition products).

Historically, the resins were used as a full mixed bed. Now, some of the plants use an anion underlay for improved sulfate control. Anion resin used with Dow cation resin is typically a high capacity resin with a Gaussian particle distribution, while the anion resin used with the IRN-99 is a high capacity uniform particle size resin. Dresden and Oyster Creek have begun using a macroporous anion resin overlay for enhanced removal of soluble Co-60.

Industry Issues

Septa Integrity

One difference between condensate filter septa and RWCU F/D septa, whether in precoat or non-precoat application, is that condensate filter septa must be replaced within three to five years after installation. This is due to fouling from iron crud which leads to increased flow resistance (dP). In addition, pleated septa in condensate precoat applications may become a sulfate source as cation resin fines may become trapped in the pleats, releasing organic sulfate due to age-related decomposition/desulfonation, necessitating septa replacement prior to end of useful life (based on run length).

In RWCU service, increased dP through the septa as a result of fouling does not occur. Generally, the RWCU system was designed with a maximum allowable dP of 25 psi through the septa. Plants typically operate well below this value, usually in the 1-5 psi range, even when precoats have been in service over 60 days. With the understanding that operating septa dPs are low, RWCU F/D septa operate significantly longer than condensate filter septa. It is not uncommon for plants to have the same set of septa in RWCU service for more than twenty years. FitzPatrick and Oyster Creek have been operating with the same sets of Purolator Poroplate™ septa for about fifteen years. Pilgrim is still operating with the original Delaval design septa.

Periodic visual inspections of RWCU F/D septa are not performed because of the potential dose associated with having to open vessels and removing septa and/or the tube bundle. As a result, the physical condition of the septa is often unknown and can be monitored only by inference from performance data.

Most RWCU F/Ds operate at pressures greater than reactor pressure. The typical operating pressure is between 1150 and 1200 psig (reactor pressure plus RWCU circulating pump discharge pressure). After a precoat has been completed and an F/D has been placed on a holding pump, the F/D must be pressurized prior to placing in service from 50-100 psig to 1150-1200 psig. The F/Ds are pressurized by opening of the inlet valves. The systems are designed with both a manual and air-operated inlet valve. The inlet piping and valves are typically 3- or 4-inch diameter.

Rapid pressurization of a F/D was identified as a potential mechanism for fouling, resin leakage, precoat disruption, and septa damage in General Electric Services Letter (GE SIL) #159 [4]. The original system designs were not conducive to preventing rapid pressurization of the F/D vessels. SIL #159 recommended modifications to install speed controls on the inlet air-operated valves to control the valve opening time. This recommendation was subsequently superseded by the industry to install a small (1/2-inch diameter) manual bypass line with isolation valve around one of the inlet valves to allow for slow manual pressurization. This change was made because the industry concluded that slow opening of a large diameter valve was not effective in controlling the pressurization of the F/Ds. A number of plants have installed the small manual bypass modification and have had this modification installed for a number of years. Recent installations of this modification include Cooper in 2006 and Nine Mile Point 2 in the fall of 2008.

The pressurizing bypass installation at Nine Mile Point 2 was in response to observed resin leakage after precoating the RWCU F/Ds with an overlay of consisting of a ground macroporous resin component. The station had historically experienced hydraulic transients when pressurizing and placing RWCU F/Ds in service. During the spring of 2006, when attempting to use the alternate precoat formulation, resin leakage was identified through three of the four F/Ds when the dP increased in the resin post strainers, located downstream of the F/Ds. In several instances, the dP reached the alarm annunciation set point. Increasing post strainer dP continued to occur on three of the F/Ds even when standard precoat materials were used. The tube bundle was removed in the "C" F/D in the summer of 2006 and was found to have significant damage. Thirteen septa were replaced and the bottom support grid was bent in several places and had to be repaired. Some tie rods were also bent. The station continued to occasionally experience increasing post strainer dP trends on all four F/Ds throughout the remainder of 2006 and into 2007 and eventually began replacing the entire septa tube bundle in each F/D. By early 2009, three of the four F/Ds had new tube bundles. The combination of not having installed the initial pressurization modification in conjunction with using ground macroporous resin caused resin leakage and septa damage. The septa used in the Nine Mile Point 2 RWCU F/Ds are the Purolator Poroplate™ design. This is the first known application where damaged Poroplate™ septa were identified. Fermi had replaced their original Poroplate™ septa bundles in 2004 with the same design. The septa were replaced because fouling was suspected. Fermi is the only BWR using 20 micron Poroplate™ septa; the rest of the top tubesheet BWRs using the Poroplate™ design use 64 micron septa. None of the plants with the Poroplate™ 64 micron septa has reported fouling.

One way to determine whether damaged septa are present is to sample the return line to the precoat tank during precoat application. Several one-liter samples can be collected at regular intervals during the time period that the precoat is being applied. The samples can then be taken to the laboratory and filtered and examined under a microscope for the presence of resin fines. Indicator dyes can also be used to identify the type of resin (cation or anion) present. Sample collection should start a few minutes after resin addition has started. The first few samples should have the most resin particles present. As the precoat progresses, if there is no significant septa damage, subsequent samples should have fewer and fewer resin particles. Few resin particles should be present at the end of precoating. FitzPatrick had performed such a sampling program in the spring of 2007 on both F/Ds as part of a troubleshooting plan to determine the cause of poor precoats. Particle counts of the collected membrane filter samples after the precoat material was applied were low (< 10 particles). Nine Mile Point 2 also performed similar

sampling during 2006 as part of their troubleshooting plan to determine the cause of the rising post strainer dP trends. Particle counts of several samples from the F/Ds suspected of resin leakage after the precoat material was applied were greater than 200. On some occasions, the precoat pumps were allowed to continue to circulate water through the F/Ds for several hours after precoat addition had been completed. Particle counts still remained high even with the extra circulation time to allow for resin particles to incorporate into the precoat.

Because RWCU septa are replaced infrequently, it is important that plants perform sampling during the precoat process, particularly those plants that have not installed the modification to control the initial F/D pressurization. Plants that still have first generation septa in service may also want to consider septa replacement. The original Delaval septa had reduced precoat area because of the spiral weld seam and were structurally deficient because the filter mesh consisted of only a single layer. In 1993, FitzPatrick observed that the Delaval septa tube bundle for one of the F/D vessels was hour-glass shaped, with a number of septa removed from the bottom support grid and some broken septa.

The woven wire septa design used in the bottom tubesheet designs was subject to resin fouling of the inner core. The upgraded micro-slot design is subject to potential structural concerns as industry experience has shown that over time ion exchange resin can degrade the nickel and stainless bond resulting in delamination of the nickel.

LaSalle 1 and 2 were the first bottom tubesheet plants to upgrade to the Poroplate™ design. Pilgrim is presently in the design phase of a project to upgrade the original Delaval septa. Susquehanna has installed the Poroplate™ design in the Unit 2 “A” vessel and is planning a similar installation in the other Unit 2 vessel as well as the Unit 1 vessels.

Precoating

The two tank Delaval system design offers one processing advantage over the single tank Graver design. In the two tank design, the addition of precoat material from the resin feed tank to the precoat piping loop is metered at a slow constant rate, resulting in a greater probability of a uniform precoat. With the Graver bottom tubesheet design, slow metering of precoat slurry can only be achieved by ensuring the “X” and “Y” valves are positioned properly and by ensuring that operators slowly add the bags of precoat material to the precoat tank in a simulated metered precoat process. This simulated metered precoat process involves adding some material, waiting for a specified time interval, and then adding more material, until the desired amount of precoat material is added. With a higher precoat pump flow, the rate of precoat application with the Graver design is significantly higher than with the Delaval design.

The bottom tubesheet designs are more prone to precoat erosion due to the vessel internal flow characteristics. As with the bottom tubesheet condensate filters, as flow passes through the inlet pipe above the tubesheet, it is deflected radially outward by the baffle plate. This creates high velocities and turbulence near the bottom of the outer septa rings. Towards the top of the septa, the velocities are significantly lower. Modeling has shown that the velocities at the bottom of the septa are an order of magnitude greater than at the top of the septa. This large difference can lead to uneven precoating and precoat erosion. To address this issue, draft tubes were installed in the center of the vessels, diverting the inlet flow from the bottom of the vessel to the top of the

vessel. Draft tube installations typically were done with bottom tubesheet condensate F/Ds but not with RWCU F/Ds, although one or more bottom tubesheet RWCU F/D vessels at Laguna Verde have draft tubes installed.

Peach Bottom 2 was the first U.S. BWR to install integrated flow distributors (IFDs) in their bottom tubesheet condensate F/Ds to improve the internal flow characteristics. Testing of the first CFD with an IFD showed a significant improvement in run lengths to a given dP endpoint. The IFD contains a modified distribution tube, a modified baffle plate, and customized upper perforated plates for the purpose of improving precoat utilization and reducing the likelihood of precoat erosion. As of spring 2009, eighteen of the twenty CFDs at Peach Bottom have IFDs installed. The Susquehanna station was the first U.S. BWR to install an IFD in an RWCU F/D. The IFD was installed in the 2A vessel at the same time the new Purolator septa were installed.

Data comparing the performance of the Susquehanna Unit 2 RWCU F/Ds is shown in Figure 11-1. Both F/Ds were precoat on the same day with two containers of a 9:1 resin/fiber premix. The data shown in Figure 11-1 were obtained 45 days into the run for each F/D. The removal efficiency of the 2A filter, with IFD and new septa, was significantly better than the 2B filter which did not have the installed modifications. The station's current plans are to perform similar modifications on the other three RWCU F/Ds.

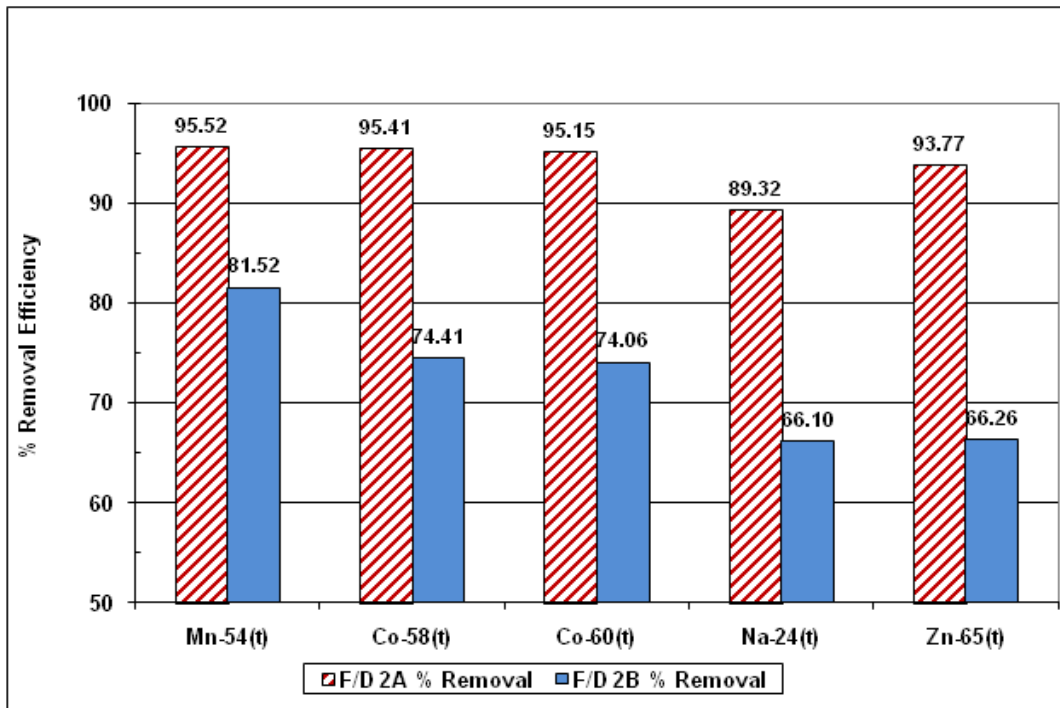


Figure 11-1
Susquehanna Unit 2 RWCU removal efficiency (2A with IFD and Poroplate septa)

Equipment problems, particularly valve problems, can impact the quality of a precoat and result in inconsistent F/D performance. One of the most common problems experienced is air intrusion or restoring an F/D to service that has not been completely filled and vented. In 2002 – 2003, FitzPatrick was achieving poor precoats due to air leaking into one F/D vessel from the air bump

valve used for backwash initiation. Air trapped in an F/D vessel will prevent precoating of the upper portions of the septa which will result in poor F/D effluent chemistry when the F/D is placed in service. Fermi has also experienced poor precoats due to air trapped in the vessels. It is important to ensure that the F/D vessels and piping are completely filled and vented prior to the start of precoating. At most plants, the F/D vessels are located at the highest point of the RWCU system. Sight glasses are typically provided on the F/D vent lines to assist the operator in determining whether the F/D vessel is completely filled with water. For top tubesheet plants with resin feed tanks, it is important that the water level in the tank be maintained above the outlet nozzle connection to prevent drawing air into the eductor and into the precoat loop.

Na-24 leakage is a useful indicator of the quality of an RWCU F/D precoat. Because the half-life of Na-24 is short (15 hours), elevated concentrations of Na-24 at the effluent of the F/Ds soon after a new precoat has been placed in service indicate that the septa are not properly precoated. FitzPatrick and Fermi routinely perform isotopic sampling of the F/D effluents and typically see Na-24 DFs greater than 200 soon after a new precoat has been placed into service.

Alternate Precoats/Resins

Within the past few years, there has been increased industry focus on using alternate powdered and bead resins to enhance the removal of Co-60. It has been postulated that in cold shutdown conditions, a significant fraction of Co-60 may be colloidal and thus may not be effectively removed by conventional precoat materials and application methods.

A summary of available industry data on the use of the alternate precoats and resins for enhanced Co-60 removal during shutdown evolutions was first published in 2007 in the EPRI BWR Shutdown Chemistry Experience Report and Application Guidelines [5]. Examples of alternate materials used for F/Ds include powdered cation resin overlays where the material has been treated by a proprietary process to enhance colloidal Co-60 removal, powdered anion resin overlays, and overlays consisting of cation enriched premix where a portion of the cation resin is a low crosslinked cation resin. Plants with RWCU deep beds have used an overlay of macroporous anion resin. Experience is further updated in BWRVIP-225: BWR Shutdown and Startup Chemistry Experience and Application Sourcebook [6].

It is noted that differences in equipment design (top tubesheet versus bottom tubesheet) and material condition (for example, septa integrity) and cation capacity of the precoats used are significant factors impacting RWCU Co-60 removal efficiency. Plants using standard precoat materials can achieve similar Co-60 removal to that of plants using specialty materials [6].

Plants should proceed with caution if intending to use an alternate precoat material that has not been used in the same application at another station. Engineering evaluations, as well as laboratory testing, should be considered prior to field implementation in such cases.

Resin Intrusions

GE SIL #159 was initiated in 1976 in response to some plants experiencing resin intrusions from the RWCU F/Ds. The following possible resin intrusion scenarios were noted [4]:

1. Loss of main circulating pump flow with the bypass line open, resulting in a siphon effect that can carry resins into the bypass line where they can later be injected into the RPV upon circulating pump restart.
2. If hold pump initiation occurs with the bypass valve open and the system is lined up for blowdown to the hotwell or radwaste, the top of the F/D vessel will empty which will result in loss of suction at the holding pump. Water and resin can then siphon into the bypass line where they can be injected into the vessel upon circulating pump restart.
3. Radical flow transients in the RWCU F/D system caused by the loss of main circulating pumps and/or the sudden opening or closing of valves. With a sudden loss of flow, there is inadequate time for the holding pumps to achieve rated speed and maintain the precoat on the elements.
4. Loss of power to the RWCU F/D system closes all inlet and outlet valves and prevents the holding pump from starting, causing the precoat to drop from the septa. With restoration of power, even with the inlet and outlet valves closed, the holding pump will start recirculating the sludge upon, into, and around the septa and holding pump circuit.
5. Sudden flow surges when placing a newly precoated F/D vessel on line will tend to cause migration of the resin particles through the filter elements.

FitzPatrick has experienced two reactor coolant sulfate spikes since 2005 that were attributed to a resin intrusion from the RWCU F/Ds. The most recent one in the fall of 2006 was the result of a main cleanup pump trip while the system was in the bypass lineup, as described in item 1, above. The pump trip occurred at the end of the 2006 refuel outage, following restoration from the RPV hydrostatic test. Sulfate spiked to 79 ppb during the initial plant heatup. The previous event occurred in July 2005 during a plant outage. The initiating event was a main RWCU pump trip when the plant was in the blowdown lineup. High dose rates developed in the blowdown line after the pump trip, indicating that resin had dislodged from the septa. Sulfate spiked to 58 ppb during the initial heatup. The event was similar to what is described in item #2, above. The station also had two siphoning events in the 1990s, where the main cleanup pumps tripped while the system was in the bypass lineup.

LaSalle 1 also experienced a siphoning event in the spring of 1996 when in the bypass lineup as a valve problem resulted in numerous trips of the main circulating pumps. Sulfate peaked at 936 ppb.

Recommendations from the SIL to mitigate the occurrence of these events were to install a strainer on the inlet piping to the F/Ds and to modify the system controls. The recommended control system modifications included [4]:

1. Modify the F/D low flow isolation logic to isolate the F/D by closing the air-operated influent valve and FCV when flow through the vessel circuit drops below 40% of the preset flow value on the first F/D and 25% on the second. This modification was intended to eliminate the resin siphoning that can lead to a resin intrusion event, as discussed above.
2. Set points for hold pump start and for the low flow annunciator should be 75% of the normal F/D vessel flow. In addition, logic should be added to automatically transfer the F/Ds into the backwash mode if the time interval between low flow annunciation and F/D system isolation is less than 15 seconds. It is not necessary to annunciate hold pump isolation since system isolation will occur before the filter cake is lost.
3. Install speed controls on the main stream inlet and outlet valves to avoid shocking the in-place precoat by limiting the intrusion of water into the F/Ds. The time for opening or closing these valves should be approximately 30 seconds. (This modification has been superseded by the manual bypass pressurization modification.)
4. Install power failure logic which will prevent the operation of the hold pump or filter until the F/Ds are backwashed. Without this logic, the hold pump will begin circulating sludge through partially precoated septa upon restoration of power which can lead to septa plugging poor precoat distribution.

A review of available drawings for a number of BWRs shows that no plants installed a strainer on the inlet piping to the F/Ds. The strainer was to be installed in the reverse direction between the NRHX and the F/Ds and would need backwash capability. Because of limited space in the piping design, it is likely that few plants, if any, installed this strainer modification.

Most BWRs were designed with electromechanical control systems for the RWCU F/Ds (valve sequencing controlled by rotating cam programmers). The above control system recommendations would be difficult to implement with this type of control system, so PLC control systems would have to be retrofitted to accomplish the above control system recommendations

Plants should be aware that resin intrusions from RWCU F/Ds can occur because of system design limitations. In order to minimize the possibility of these types of resin intrusions, plants should focus on improving the reliability of the main RWCU pumps, upgrading septa, installing the manual bypass modification (if not already done) and upgrading the F/D controls to PLC technology.

Power Upgrades

A number of plants have performed stretch or extended power upgrades over the past decade. Increasing feedwater flow as part of the power upgrade may increase the mass transport of impurities to the reactor vessel. Maintaining the same RWCU flow under power upgrade conditions decreases the rated capacity (percentage of feedwater flow) of the RWCU system.

Several plants implementing power uprates have not been able to cost justify increasing the size of the RWCU system to compensate for the increase in feedwater flow. Most plants are limited by the current capacity of the system heat exchangers. Installing larger heat exchangers would be a significant (high cost, high dose) plant modification.

Some plants have performed hydraulic and heat transfer evaluations to determine the maximum capacity obtainable with the current system design. Browns Ferry performed this evaluation in 2006 - 2007. The station concluded that the systems at each unit are capable producing a total filter flow of 300 - 310 gpm, versus the original design flow of 250 - 260 gpm. The station began operating at the higher flows in 2007 in preparation for extended power uprate. Flow has to be reduced on very hot summer days due to heat exchanger limitations.

FitzPatrick is another example of a plant that was able to increase the system flow by 19 - 20% through the performance of a detailed evaluation. This was done in the early 1990s, well before the first power uprate. The station has since routinely operated the system at the higher flow rate. Plants that have not performed a similar hydraulic and heat transfer evaluation should consider this approach, particularly as part of power uprate projects, to utilize the design capability of the system.

Power uprate projects also provide opportunities to maximize the performance and availability of the system through septa replacement, flow distribution improvements (bottom tubesheet designs), control systems upgrades and system pump upgrades, including potential relocation to the cold leg.

NMCA Effects

At some plants, implementation of NMCA has resulted in RWCU issues. Two examples of such issues are presented here.

Nine Mile Point 2

In 2002, a detailed discussion was provided on the post-NMCA RWCU operating experience at Nine Mile Point 2 [3]. The station observed elevated RWCU F/D effluent conductivity on three of the four F/Ds whenever hydrogen injection was in service. The F/D effluent conductivity for these vessels was greater than reactor coolant conductivity. When hydrogen injection was secured, the F/D effluent conductivity levels would decrease to less than reactor coolant conductivity. This anomaly was observed with the three F/D vessels that were used during the noble metal application and cleanup. It was concluded that noble metal deposition downstream of the F/D septa lowers the ECP when sufficient hydrogen is present, causing iron oxide to restructure to the soluble form.

An update of the Nine Mile Point 2 experience was included in the 2005 edition of the monitoring report [7]. The station continued to experience this anomaly through mid-2005, almost five years after the initial noble metal application. This effect has also been seen at some other BWRs, although the effect was not as long lasting as at Nine Mile Point 2.

Immediately following the first OLNC at Nine Mile Point 2 in December 2007, the effluent conductivities of the “A”, “B”, and “D” F/Ds were higher than reactor water conductivity, as shown in Figure 11-2 through Figure 11-5. The “C” F/D was initially not in service following the first OLNC and may have been out of service during the application. By the spring 2008 refueling outage, the effluent conductivities of the “A” and “B” F/Ds had decreased and were very close to reactor coolant values. The conductivity of the “D” F/D was lower than reactor water. The conductivity of the “C” F/D was higher than reactor water at the time leading up to the outage, when HWC was in service, and remained higher than reactor water for several months after the refuel outage. By the time of the second OLNC in December 2008, the effluent conductivities of all four F/Ds were lower than reactor water conductivity. After the second OLNC, most conductivity values for all four F/Ds were equal to or less than reactor water. The data trends following the OLNC applications at Nine Mile Point 2 suggest that a lower increase in RWCU effluent conductivity can be expected after each OLNC application than after NMCA. The lower amount of catalyst injected during each OLNC application apparently results in less soluble iron release due to iron oxide restructuring than with NMCA.

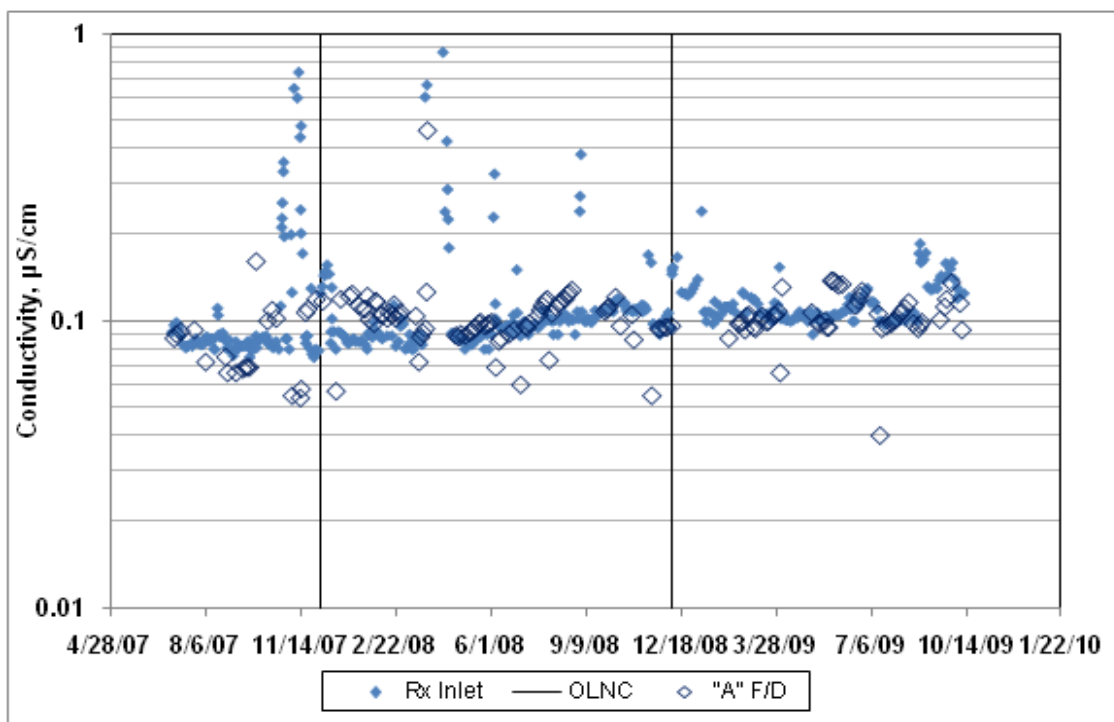


Figure 11-2
Nine Point 2 RWCU “A” F/D effluent conductivity trend

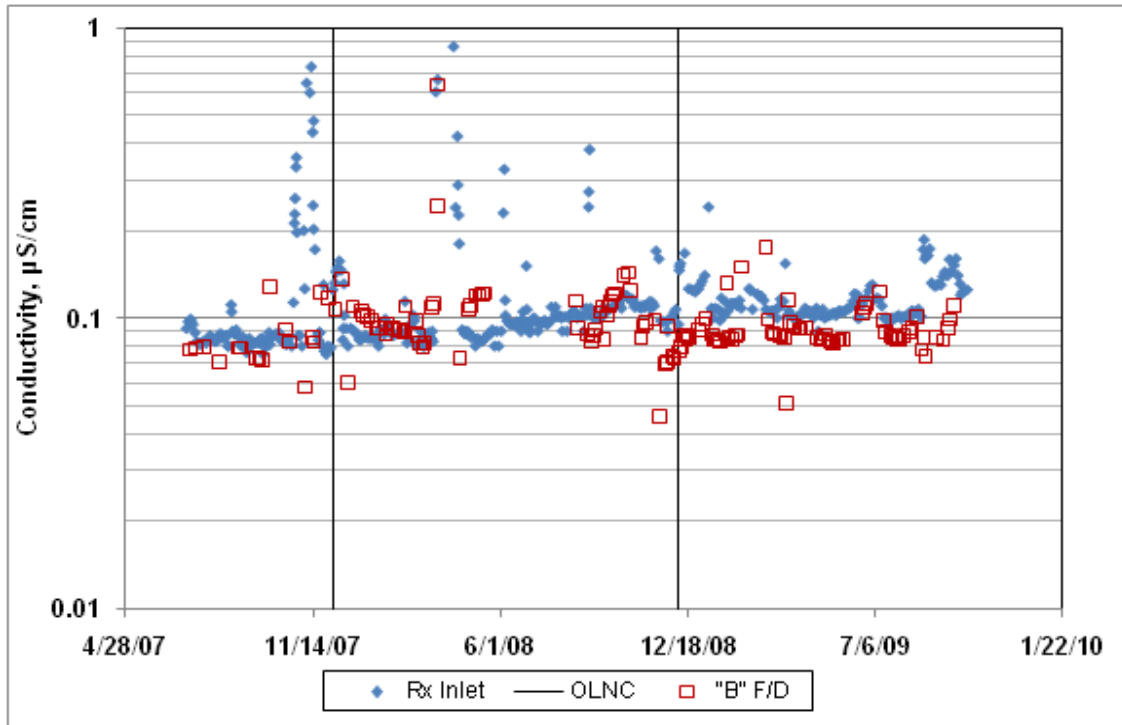


Figure 11-3
Nine Point 2 RWCU "B" F/D effluent conductivity trend

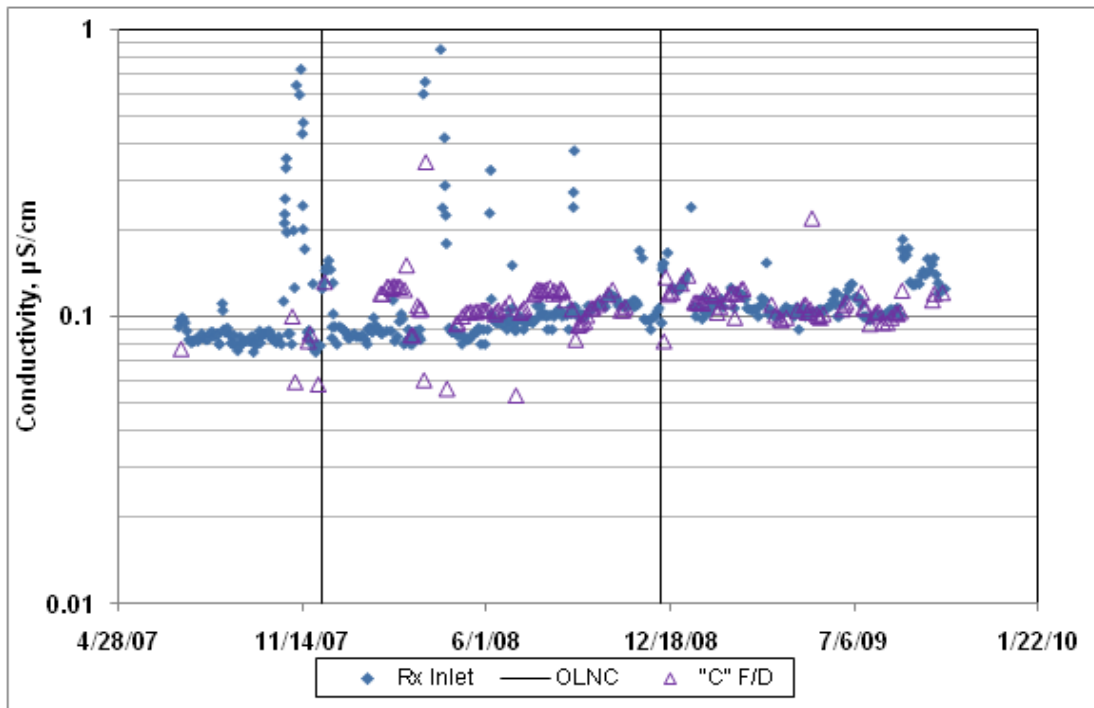


Figure 11-4
Nine Point 2 RWCU "C" F/D effluent conductivity trend

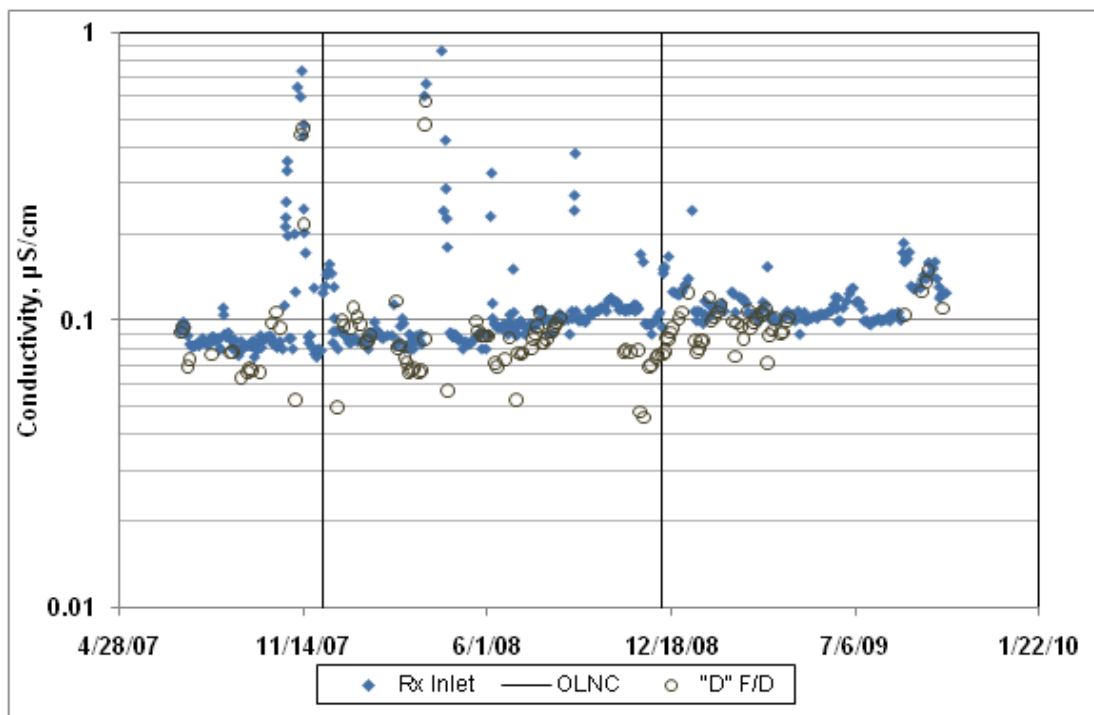


Figure 11-5
Nine Point 2 RWCU "D" F/D effluent conductivity trend

Laguna Verde

NMCA was first performed at Laguna Verde 1 in September 2005 and Laguna Verde 2 in April 2006. Neither unit had operated with hydrogen injection prior to the application. Hydrogen injection was first initiated at Unit 1 in December 2005 and at Unit 2 in June 2006. The target hydrogen injection rate to produce a molar ratio of hydrogen to total oxidants of greater than 2:1 is 7.5 scmh (standard cubic meters per hour, equivalent to 4.4 scfm).

After starting hydrogen injection to the feedwater at the target rate of 7.5 scmh, both units observed a gradual decrease in RWCU system flow rate over time. The RWCU flow rate returned to the normal rate after hydrogen flow was lowered. The RWCU flow did not decrease from the normal rate when the hydrogen injection flow was maintained at or below 5 scmh for Unit 1 and 4 scmh for Unit 2, which corresponds to 67% and 53%, respectively, of the current target hydrogen injection rate of 7.5 scmh. The station reported venting an unidentified gas at a high point of the RWCU piping at each unit while troubleshooting the RWCU flow problem and suspected that hydrogen gas was coming out of solution. A plot of Unit 2 RWCU flow is shown in Figure 11-6. The solid red line shows that hydrogen was being injected at a flow of about 7 scmh. The blue line is the total RWCU flow from the plant process computer. During this time period, the flow decrease was about 0.5% per day.

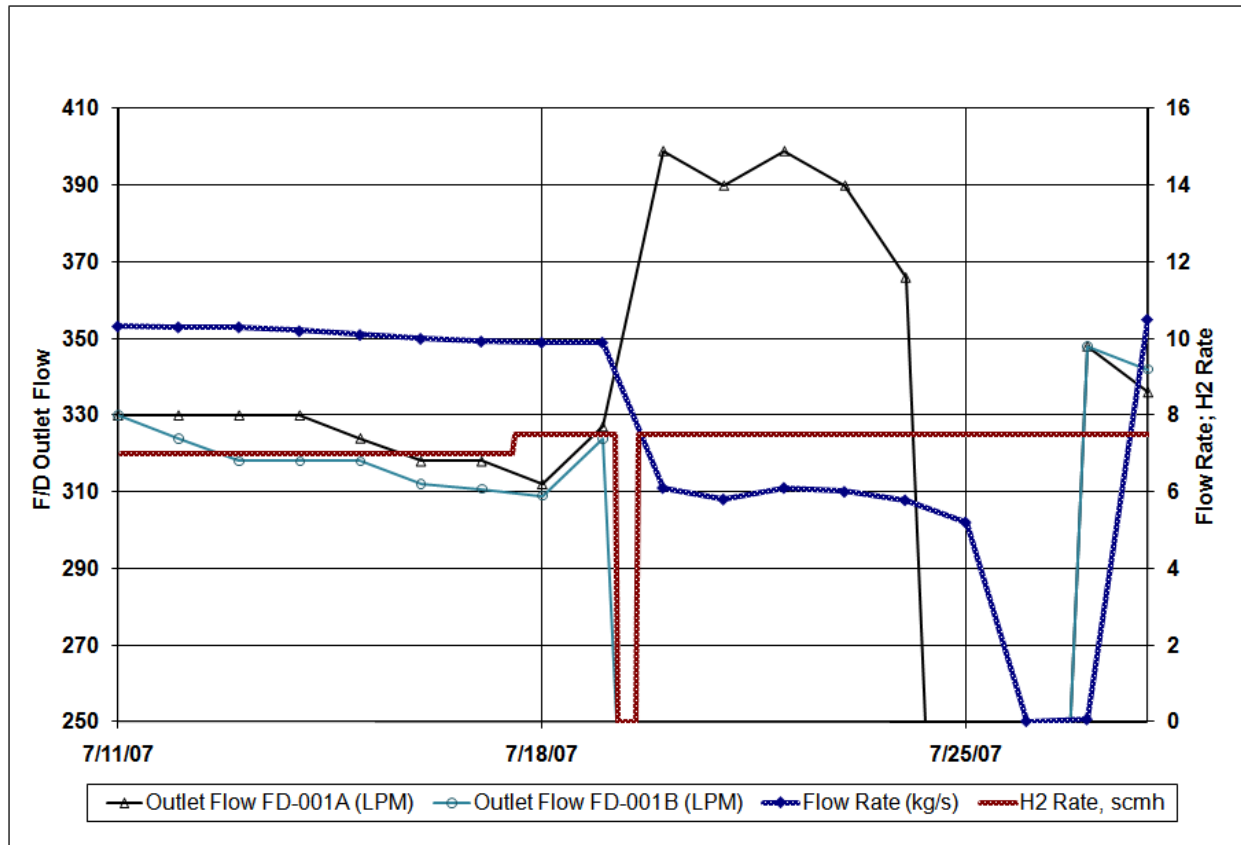


Figure 11-6
Laguna Verde 2 RWCU flow – July 2007

The RWCU systems at the Laguna Verde units contain bottom tubesheet filter/demineralizers. The piping design is similar to other BWRs where each RWCU system takes suction from the reactor recirculation system piping and the RPV bottom head drain. The main circulating pumps are located on the “hot leg”, upstream of the Regenerative Heat Exchanger. One pump is required for operation to achieve rated system flow. The outlet of the F/Ds returns to the shell side of the Regenerative Heat Exchanger and then returns to final feedwater.

As in most RWCU system designs with F/Ds, filtration flow is controlled by flow control valves at the effluent of the F/Ds. These flow control valves automatically open in response to lower upstream pressure, such as high dP across the F/D and/or the post strainer. Field observations indicated that the flow control valves were between 20 and 23% open.

Investigation into the Laguna Verde RWCU anomaly focused on hydrogen gas solubility, RWCU system hydraulics, and HWC+NMCA chemistry [8]. A review of hydrogen gas solubility ruled out the possibility of hydrogen degassing at the operating temperatures and pressures at various locations throughout the RWCU system.

Hydraulic modeling of the RWCU system identified that a four-inch diameter valve located on the outlet side of the Regenerative Heat Exchanger (return to feedwater) at both units gives a dP of about 28.5 psi when the valve is wide open. The equivalent sharp-edge orifice size of the throttled valve was about 1.41 inches in diameter. The valve is often used in a throttled position, so the dP would be higher and effective opening size lower.

The BWRVIA Version 2 radiolysis model was run for Laguna Verde 1 with data inputs received from the station. The initial results showed that at a hydrogen flow of 4 - 5 scmh, the molar ratio is less than 2 and that at a flow between 6.7 and 6.8 scmh, the molar ratio is greater than 2 in the RWCU system.

Station chemistry data showing elevated RWCU F/D conductivity after hydrogen injection was placed in service at both units indicated the presence of noble metals on the effluent side of the F/Ds where they deposit on surfaces, creating reducing conditions at the surfaces when the hydrogen: oxidants molar ratio is >2 , promoting the formation of soluble iron that leads to a conductivity increase. This type of response has been seen at plants with carbon steel F/D effluent chambers or piping [3, 7].

With the elimination of the possibility of hydrogen degassing, the fact that RWCU flow would be steady at hydrogen injection rates ≤ 5 scmh but decrease when the injection rate was increased to the level where the molar ratio was > 2 , combined with the likelihood of noble metal on the effluent side of the F/Ds based on conductivity data, led to the conclusion that the probable cause may be related to crud oxide restructuring. Specifically, when sufficient hydrogen is added, oxide restructuring can lead to the release of soluble iron and crud which can deposit on other surfaces, especially those that are already restricted in flow area, for example, the throttled Regenerative Heat Exchanger effluent valves.

Based on the BWRVIA model results which showed that mitigation was not being achieved at a flow of 5 scmh, a recommendation was made to increase hydrogen flow by small increments over an extended period of time until the desired flow rate was reached. If the cause was related to crud restructuring, it was concluded that the problem would eventually resolve itself based on other NMCA industry experience. Such an approach was implemented at Unit 1 in the spring of 2009. The station was able to eventually raise the hydrogen flow to 7.5 scmh without observing RWCU flow decreases. A similar plan was recommended at Unit 2 following the spring 2009 refuel outage.

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12

BWR WATER CHEMISTRY GUIDELINES ISSUES

BWRVIP-190: BWR Water Chemistry Guidelines – 2008 Revision was issued in October 2008. BWRVIP-190 was transmitted to BWRVIP members by BWRVIP Letter 2008-326, which required implementation by May 31, 2009. In 2010, an interim review will be conducted to discuss issues that have been raised since implementation, and to determine their disposition. The issues received to date are listed in Table 12-1, arranged in order of the applicable chapter of the 2008 Guidelines. Future issues will be added to this list for consideration in the 2010 interim review. The next full revision is scheduled for 2012.

Table 12-1
Issues for 2010 interim review of BWR water chemistry guidelines

Item	BWRVIP-190 Reference	Issue	Comments
O-1	Overall	Guidelines are currently only for BWR 2-6 designs. Can/should recommendations be included for ABWRs?	STP is planning to build two ABWRs. There are also several operating ABWRs in Japan. These plants also need guidance and should be included in future Guidelines, as possible.
O-2		Duane Arnold has a requirement to ensure that the plant is at greater than 15% power AND feedwater temperature is greater than 200°F before putting zinc system in service to avoid thermal shocks causing zinc pellet cracking and fracturing when the plant does the turbine trip test on startup. Experience described in Section 7 of the SD/SU Sourcebook does not seem to address this topic.	No current guidance in Guidelines. Consider addition of Startup Chemistry appendix similar to the current Appendix B for Shutdown Chemistry Recommendations.
2-1	Chapter 2	More low temperature CGR data would be useful.	Some data is available; this should be looked at in future Guidelines with appropriate recommendations as needed.
2-2	Chapter 2	Impact of NRC review of BWRVIP-62 should be part of next Guidelines revision.	NRC review of BWRVIP-62 and BWRVIP response is still underway. Guidelines impacts will be addressed in future review and revisions as appropriate.
2-3	Chapter 2	Low impact startups need to be addressed, considering strategies such as hydrazine injection or early HWC. The need for some crack growth data vs. ECP as a function of temperature to validate options should be considered.	Data are limited; maybe more will be available by 2012, including E-HWC demonstration at Peach Bottom.
2-4	Chapter 2	Include a clear statement that having a Mitigation Performance Indicator is "needed" and consider incorporation of the BWRVIP's MPI in the Guidelines.	Include in 2.7.1 - Parameters to Verify Mitigation of IGSCC. Consider adding to Chapters 6 and 7.

Table 12-1**Issues for 2010 interim review of BWR water chemistry guidelines (continued)**

Item	BWRVIP-190 Reference	Issue	Comments
3-1	Chapter 3	Additional guidance on Co-60(s)/Zn(s) ratio control is needed to balance fuel concerns: Plants are being driven to achieve a low Co/Zn ratio by imposing Co/Zn goals driven by chemistry performance indicators. Some plants may be forced to add more Zn than really needed to satisfy a performance indicator.	More work is needed in this area, and a project is planned for 2009 - 2010 to review zinc strategy. The expectation that more plants will implement OLNC, with annual applications, should be taken into account.
3-2	3.3.1 General Description of Co-60 Transport Processes in the BWR Primary System; 7.3 Reactor Water Goals; Table 8-1 Recommended chemistry database parameters	Increased W-187 in reactor coolant may be an indicator of Stellite corrosion/erosion.	Add a discussion; considering monitoring W-187 if Stellite degradation is thought to be contributing to increased reactor coolant Co-60.
5-1	Chapter 5	More experience from European plants on fuel crud and performance is desired, especially for the very low iron plants.	Very little data is available; this should be looked at in future Guidelines with appropriate recommendations as needed.
5-2	Chapter 5	Spalling and FW Zinc: New data from fuel examinations from the higher FW zinc plants should become available in 2 to 3 years to help flesh out this relationship. Data from plants that use high zinc at startup, especially after a fresh NMCA application, would be useful. More data from HWC-M plants could provide the basis to revise their FW Zn spec as well.	Additional fuel surveillance data are required.
5-3	Chapters 5 (and possibly 6 & 7)	Fuel performance can be impacted by power density. Can this be included in future Guidelines?	Will work with fuel community on this area for future Guidelines considerations.
6-1	Chapter 6	Phosphates have an impact on CGR. Should future Guidelines make recommendations or have Action Levels for this specie?	Some data is available; this should be looked at in future Guidelines with appropriate recommendations as needed.
6-2	Section 6	Table Numbers: Table 6-5a is missing the "a". The same situation occurs for Table 6-6.	Make editorial changes.

Table 12-1**Issues for 2010 interim review of BWR water chemistry guidelines (continued)**

Item	BWRVIP-190 Reference	Issue	Comments
6-3	Table 6-3	Conductivity Correction for Zinc at Startup: Reactor water conductivity may exceed 1 $\mu\text{S}/\text{cm}$ during startup when temperature goes above 200°F due to Zn (Startup/Hot Standby). The Guidelines do not address conductivity correction for Zn at this point.	Effects of elevated pH at high conductivity on cracks and potential fuel impacts need to be considered.
6-4	Table 6-3	Table 6-3 typographical errors: In Table 6-3, it has already been identified that the notes in the right hand column of the table should be (c) and (d) rather than (a) and (b).	Corrected; BWRVIP Letter 2008-326 issued June 29, 2009
6-5	Chapter 6 and Chapter 7	Inconsistencies with Use of < and $\leq$: In BWRVIP-130, rx water conductivity goal was <0.08 and in BWRVIP-190, it is $\leq$ 0.08. While conductivity has $\leq$ value, other parameters such as chloride and sulfate have only <. So, for sulfate, a value of 2.0 would be outside the range for optimum water chemistry, but 1.99 is not. In Table 6-6c, HWC goals are given as >95 and >98 whereas the BWRVIP mitigation PI gives a "green" value for $\geq$95 and $\geq$98.	These signs should be reviewed. The symbols $\leq$ and $\geq$ should be used instead of underlined characters because the underline may be lost.
8-1	Table 8-1	Measurement of N-13 in Offgas Samples: Consider including the measurement of N-13 in offgas samples. The fraction of N-13 that goes to offgas changes with HWC and affects the ratio that plants apply to the offgas radiation level to estimate fission gas release between offgas sampling.	Are there any reporting requirements for N-13 (10 minutes half-life)? Some discussion of the effects of HWC on N-13 activity in offgas and its effect on the offgas radiation monitor may be useful.

Table 12-1**Issues for 2010 interim review of BWR water chemistry guidelines (continued)**

Item	BWRVIP-190 Reference	Issue	Comments
8-1	Table 8-1 notes; 8.3.7.1 Monitoring Approaches (Corrosion Products and Zinc)	If the zinc being measured in feedwater and reactor water is depleted zinc, and the analysis instrument (either XRF, ICP or AA) is calibrated using natural zinc standards, the reported zinc concentrations must be biased.	Add brief discussion to be sure that chemists are aware of this and suggest approaches to eliminate this source of error.
8-2	Section 8.3.8	Co-60 Measurement Practices: The KKL method of pretreating a membrane filter with KNO_3 prior to filtration of reactor water for isotopic analyses is apparently unique among BWR chemistry practices and leads to a significantly different distribution between soluble and insoluble activities in a reactor water sample, compared to the remainder of the fleet. Membrane filters with a pore size smaller than the conventional 0.45 μm for separation of soluble and insoluble activities have also been used by some plants.	Since KKL is now an NMCA plant, GEH has said they should be controlling the reactor water Co-60/Zn ratio to less than $1.4\text{E-}5 \mu\text{Ci/ml/ppb}$ to be more in line with industry guidance for dose control. Consider amplifying Section 8.3.8, possibly including a table of variables of sampling practices by plant and discuss effects on sample results.
8-3	Section 8.4	ECP: A new discussion of ECP measurement (where to measure and how), its implications and how one responds to different scenarios encountered would be worthwhile. Since the overall objective of the guidelines is to mitigate IGSCC damage and ECP is one of the key variables affecting IGSCC initiation and propagation, the discussion and treatment in the guidelines needs to be taken to a "higher level."	Information should be reviewed and expanded as appropriate. Startup ECP should be addressed.

Table 12-1**Issues for 2010 interim review of BWR water chemistry guidelines (continued)**

Item	BWRVIP-190 Reference	Issue	Comments
8-4	Section 8.4	Use of Pt ECP Electrodes to Confirm Mitigation in NMCA Plants: There is a problem with using a platinum reference electrode to measure the ECP of a stainless steel surface treated with noble metal. When there is sufficient hydrogen (molar ratio at the surface of the reference >2), the "raw" potential difference between the stainless steel and the reference is within a few millivolts of zero, and most of the variation in ECP(SHE) is due to variations in the hydrogen concentration. When there is insufficient hydrogen, there may be a shift in the "raw" difference of perhaps 20 millivolts, but if hydrogen is being injected and the hydrogen concentration estimated from the injection rate, the calculated ECP(SHE) will still be well below -230 mV(SHE), although IGSCC may not be mitigated. Also an open failure in the circuitry will also give a "raw" value of zero. It is important that the condition of the reference be checked periodically by measuring the impedance. The value of the iron-iron oxide reference is that its functionality is independent of the molar ratio, and that it is obvious from the "raw" values when the probe has begun to fail.	The difficulties of determining whether IGSCC is mitigated based on measurements of ECP when only Pt reference electrodes are available should be discussed in the Guidelines. Possible recommendations include: • periodic impedance measurements • periodic calibration or calibration checks on the electronics • regular measurements of reactor water hydrogen and oxygen to demonstrate that the molar ratio is >2 and that the excess hydrogen is above a specified limit (perhaps 15 ppb).

Table 12-1**Issues for 2010 interim review of BWR water chemistry guidelines (continued)**

Item	BWRVIP-190 Reference	Issue	Comments
8-5	Section 8.7	Moisture Carryover Impacts: Moisture Carryover is critical for several issues that the BWRs are facing and the Guidelines do not have a limit. We should have some comments on its determination methods. May want to put some thought into Main Steam sampling as well if Hatch's turbine cracking could be from carryover. Impact of fuel design changes on moisture carryover should be considered.	Effects of fuel design and potential corrosion of turbine components need to be addressed. A scoping study of industry experience with moisture carryover and its impacts is in progress, report to be issued in 2010. Additional EPRI studies should be available for the 2012 Revision.
C-1	Appendix C	Durability Monitor Coupons for OLNC: During a future Chemistry guideline update, information should be provided on durability coupon removal strategy similar to the NMCA coupon strategy for analyzing a coupon every 6 months. With more plants planning to go to OLNC applications, coupon guidance is needed.	Catalyst loading is discussed in the BWRVIP report by GEH: Technical Basis for On-Line NobleChem™ Mitigation and Effectiveness Criteria for Inspection Relief
F-1	Appendix F	AREVA would like to support future review/revisions of Appendix F (conductivity corrections).	AREVA will be part of the team for this area in the future.

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Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com