Enclosure 4

PWR Secondary Water Chemistry Guidelines
Revision 6

Non - Proprietary Version

Pressurized Water Reactor Secondary Water Chemistry Guidelines - Revision 6

Technical Report

Pressurized Water Reactor Secondary Water Chemistry Guidelines – Revision 6

1008224

Non- Proprietary Final Report, December 2004

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Pressurized Water Reactor Secondary Water Chemistry Guidelines – Revision 6, EPRI, Palo Alto, CA: 2004. 1008224.

REPORT SUMMARY

State-of-the-art water chemistry programs reduce equipment corrosion and enhance steam generator reliability. A committee of industry experts prepared these revised *PWR Secondary Water Chemistry Guidelines* to incorporate the latest field and laboratory data on secondary system corrosion and performance issues. PWR operators can use these guidelines to update their secondary water chemistry programs.

Background

EPRI updates industry water chemistry guidelines periodically as new information becomes available. Previous versions of these *PWR Secondary Water Chemistry Guidelines* identified a detailed water chemistry program deemed consistent with the then-current understanding of research and field information. Each revision discussed the impact of these guidelines on plant operation, noting that utilities may wish to revise the presented program following a plant-specific evaluation for implementation. Utility feedback since publication of Revision 5 in May 2000 revealed that some utility chemistry personnel required further details regarding how to best integrate these guidelines into plant-specific optimization process while still ensuring compliance with NEI 97-06 and NEI 03-08.

Objective

To update the *PWR Secondary Water Chemistry Guidelines—Revision 5.*

Approach

A committee of industry experts, including utility specialists, nuclear steam supply system vendor representatives, Institute of Nuclear Power Operations representatives, consultants, and EPRI staff, collaborated to review the available data on secondary water chemistry and secondary cycle corrosion. From these data, the committee generated water chemistry guidelines that utilities should adopt at all PWR nuclear plants. Recognizing that each nuclear plant owner has a unique set of design, operating, and corporate concerns, the guidelines committee developed a methodology for plant-specific optimization.

Results

Revision 6 of the *PWR Secondary Water Chemistry Guidelines* provides recommendations for PWR secondary systems of all manufacture and design, and includes the following chapters:

- Chapter 1 contains a list of management responsibilities and addresses secondary water chemistry program requirements for compliance with NEI 97-06 (SG Program Guidelines). It also identifies the parts of these Guidelines that are mandatory, "shall" requirements, and recommendations, consistent with NEI 03-08.

- Chapter 2 presents a compilation of corrosion data for steam generator tubing and, to a lesser extent, balance-of-plant materials. This information serves as the technical basis for the specific parameters and programs detailed in the document.
- Chapter 3 discusses the role of the concentration processes in local regions of the steam generator and the chemistry programs available for minimizing the impact of impurity concentration. It briefly identifies the supporting aspects and considerations in adopting these chemistry regimes.
- Chapter 4 presents a detailed method for performing plant-specific optimization, including development of a modified chemistry program.
- Chapters 5 and 6 present water chemistry programs for the recirculating steam generator (RSG) and once-through steam generator (OTSG). These are the chapters most frequently referred to by chemistry personnel. The tables in these chapters provide the boundaries for the plant-specific optimization procedures described in Chapter 4.
- Chapter 7 provides information on data collection, evaluation, and management. This chapter describes methods of using **EPRI chemWORKS ™** modules for evaluating plant data and predicting high-temperature chemistry environments throughout the cycle.
- Appendix A provides examples of methodologies for implementing integrated exposure programs.
- Appendix B provides the results of a recent review of PWR steam chemistry considerations.

EPRI Perspective
This sixth revision of the *PWR Secondary Water Chemistry Guidelines*, endorsed by the utility executives of the EPRI Steam Generator Management Program, represents another step in maintaining proactive chemistry programs to limit or control steam generator degradation, with consideration given to corporate resources and plant-specific design/operating concerns. Each utility should examine its plant-specific situation to determine which recommendations to implement.

Keywords
PWR
Water chemistry
Corrosion protection
Nuclear steam generators
Secondary coolant circuits

EPRI FORWARD

Industry water chemistry guidelines are updated periodically as new information becomes available. Previous revisions of these guidelines have identified a detailed water chemistry program that was deemed to be consistent with the then current understanding of research and field information. Each revision, however, has recognized the impact of these *Guidelines* on plant operation and has noted that utilities should optimize their program based on a plant-specific evaluation prior to implementation. To assist in such plant-specific evaluations, Revisions 4 and 5, issued in 1996 and 2000, respectively, provided an increased depth of detail regarding the corrosion mechanisms affecting steam generators and the balance of plant, and provided additional guidance on how to integrate these and other concerns into the plant-specific optimization process. Revision 6 retains the format of Revisions 4 and 5, and adds to the detailed information contained in these revisions. The chapters of Revision 6 cover the following:

- Chapter 1 identifies Management Responsibilities. It also describes which elements of the *Guidelines* are mandatory and "shall" requirements under NEI 03-08, Guideline for the Management of Materials Issues, (consistent with NEI 97-06) and which are recommendations.
- Chapter 2 presents a compilation of corrosion data for steam generator tubing and, to a lesser extent, balance-of-plant materials. It is not intended to relate operational bulk water chemistry to the corrosion phenomena, which is covered in Chapter 3. The corrosion data presented in Chapter 2 serve as the technical bases for each of the specific parameters and programs detailed in the balance of the document.
- Chapter 3 discusses the role of the concentration processes in the various locations of the steam generator and the chemistry "tools" available for modifying the resulting chemistry within these concentrating regions. It briefly identifies the supporting aspects of and the considerations for adopting these chemistry regimes. It refers the reader to more detailed documents for application of the chemistry strategies.
- Chapter 4 presents a detailed methodology for performing the plant-specific optimization that can be used to develop a modified chemistry program that satisfies site-specific concerns. Chapter 4 also presents example startup and operating chemistry parameters and limits that can be used as a starting point for site-specific evaluations.
- Chapters 5 and 6 present water chemistry programs for RSGs and OTSGs, respectively. These are the chapters most frequently referred to by chemistry personnel. The tables contained within these chapters provide boundaries of the envelope within which plant-specific optimization should occur.
- Chapter 7 provides information on data collection, evaluation, and management. This chapter covers use of EPRI chem*WORKS*™ modules for evaluating plant data and predicting high-temperature chemistry environments throughout the cycle.

- Appendix A provides detailed guidance with regard to use of the integrated exposure concept.
- Appendix B provides a review of PWR steam chemistry considerations.

These *Guidelines* were produced by the Committee with support from an industry Technical Review Team and the technical committees of the Steam Generator Management Program. Key technical changes in this revision include:

Keith Fruzzetti
Chairman

ACKNOWLEDGMENTS

Preparation of these guidelines required significant involvement of industry personnel to provide technical review beyond the role of the authoring committee listed on the title page. The personnel in this group of specialists, called the Technical Review Team, are listed below with their organizations for acknowledgment:

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Johnny Barker	Tennessee Valley Authority
Stephen Barshay	Westinghouse
Alan Beebe	Omaha Public Power District
Mohamad Behravesh	EPRI
Johan Blok	EPRI
Dennis Bostic	Dominion Resources
Michael Brett	COG (Ontario Power Generation)
Guy Bucci	Arizona Public Service
Dudley Carter	Southern Nuclear
Martin Cubitt	British Energy Generation
Robert Cullen	Entergy North
Nikki Delse	EPRI
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Gail Gary	AmerenUE
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Norma Gordon	Exelon
Jeff Heinold	Florida Power & Light
Rusty Hitch	Progress Energy
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1.1 Introduction and Objectives

The objective of this document is to provide guidance on determining and implementing a set of plant-specific water chemistry requirements for the secondary cycle of PWRs. Accordingly, this document presents the corrosion data that provide the technical bases for water chemistry control (Chapter 2), the various water chemistry control strategies that are available (Chapter 3), a recommended methodology for plant-specific optimization (Chapter 4), generic water chemistry guidelines for RSGs and OTSGs (Chapters 5 and 6, respectively), and suggested data collection, evaluation, and management techniques (Chapter 7).

In addition, the U.S. nuclear power industry established a framework for increasing the reliability of steam generators by adopting NEI 97-06, *Steam Generator Program Guidelines* [1, 2]. This initiative references EPRI's Water Chemistry Guidelines, including this document, as the basis for an industry consensus approach to chemistry programs. Specifically, the initiative requires that U.S. utilities meet the intent of the *EPRI PWR Secondary Water Chemistry Guidelines*. The focus of the NEI initiative is steam generator integrity. These *Guidelines* are a support document under NEI 97-06. These *Guidelines* include control parameters and monitoring requirements which must be incorporated into a plant's water chemistry program in order to meet the intent of these *Guidelines*.

1.2 Water Chemistry Management Philosophy

1.3 Generic Management Considerations

This section lists and discusses the considerations which are common to most utilities, including the elements of organizations which are needed to carry out the water chemistry program effectively. Actions are identified without specifying responsibility for completing them. Utility-specific implementation policies and procedures should assign the responsibilities to specific positions within the organization. One major element of these *Guidelines* is the need for every level of management to understand the importance of the action levels presented in Chapters 5 and 6 and their potential impact on, and benefits to, the utility company. In addition, there is a need for management to support a data collection, evaluation, and management system similar to the approach discussed in Chapter 7.

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Corrosion of steam generator tubes has been the major issue affecting selection of secondary water chemistry parameters. However, corrosion and flow-accelerated corrosion (FAC) of steam generator internals and other secondary system components are also important concerns. The objective of this chapter is to review the causes of this corrosion and FAC and to provide the technical bases for measures to control these concerns.

2.2 Introduction

This chapter of the secondary water chemistry guidelines discusses corrosion issues affecting PWR steam generators and balance of plant components, with the objective of providing bases for selecting secondary water chemistry parameters that minimize problems due to corrosion.

The objective of secondary side water chemistry control is to minimize corrosion damage and performance losses for all secondary system components and to thereby maximize the reliability and economic performance of the secondary system. To achieve this objective, the water chemistry has to be compatible with all parts of the system including steam generators, turbines, condensers, feedwater heaters, moisture separator reheaters (MSRs), and piping. The variety of materials used in the many components in typical secondary systems, and the range of temperatures, pressures, phases, and velocities place constraints on the selection of water chemistries for secondary systems.

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4.1 Introduction

Due to the wide range of conditions and materials of construction in the secondary system, no single optimum water chemistry program can be specified for all PWRs. As such, a site-specific optimized water chemistry program requires development. This program should consider factors such as steam generator and BOP component design and operating history and use of condensate and/or blowdown demineralizers. The overall objective of the optimization is to maximize the total avoided costs from corrosion and other performance related issues while minimizing operating costs. Since a cost/benefit analysis for the secondary system cannot be completed with great certainty, the approach presented here considers the relative risks/benefits of various chemistry programs on a component-by-component basis. It is recognized that tradeoffs exist whereby optimization of the water chemistry program for one component (e.g., steam generators) could negatively impact costs of operating other components (e.g., demineralizers). The relative importance of individual components should be evaluated based on utility and plant-specific considerations. The goal of this chapter of the guidelines is to provide a basis for establishing an optimized secondary water chemistry program, not to prescribe the program in detail.

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5.1 Introduction

These guidelines reflect current understanding of the role of chemical transport, impurity concentrations, material selection, corrosion behavior, chemical analysis methods, and industry practices on the operation and integrity of steam generator systems.

The guidelines included in this chapter represent a condensation of the technical bases from Chapter 2, chemical control strategies from Chapter 3, and optimization issues from Chapter 4 into a generic program for recirculating steam generators (RSG).

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WATER CHEMISTRY GUIDELINES ONCE-THROUGH STEAM GENERATORS

6.1 Introduction

The guidelines presented in this chapter reflect the current understanding of the roles of chemical transport, impurity concentrations, and materials on the operation and integrity of once-through steam generator (OTSG) systems. They also reflect the technical bases of Chapter 2, the chemical control strategies of Chapter 3 and the optimization issues of Chapter 4.

6.2 Control and Diagnostic Parameters

6.3 Action Responses

6.3.1 Action Level 1

6.3.2 Action Level 2

6.3.2.1 "Shall" Requirement Actions

6.3.3 Action Level 3

6.4 Status Modes

6.5 Guidelines

6.5.1 Cooldown/Hot Soaks

6.5.2 Cold Shutdown/Wet Layup

6.5.2.1 Guidelines/Technical Justifications

Table 6-1
Full Wet Layup (RCS ≤200°F) (Technical Specification Modes 5 and 6) Steam Generator Sample

Table 6-2
Once-Through Steam Generator Fill Water

6.5.2.2 Parameter Justifications

6.5.2.3 Corrective Actions

6.5.3 Startup, Hot Standby, and Reactor Critical at <15% Reactor Power (RCS >200°F, <15% Reactor Power) – Modes 1, 2, 3 and 4 of STS

6.5.3.1 Guidelines/Technical Justifications

Table 6-3
Once-Through Steam Generator Startup/Hot Standby/Reactor Critical at <15% Reactor Power (Technical Specification Modes 1, 2, 3 and 4) Feedwater Sample

Table 6-4
Once-Through Steam Generator Startup/Hot Standby/Reactor Critical at <15% Reactor Power (Technical Specification Modes 1, 2 and 3 and Mode 4 During Startup)
Blowdown Sample*

6.5.3.2 Parameter Justifications

6.5.3.2.1 Feedwater

6.5.3.2.2 Steam Generator Bulk Water

6.5.3.3 Corrective Actions

After verification that a parameter is not within normal limits, the following corrective actions should be considered:

6.5.4 Power Operation (≥15% Reactor Power)

6.5.4.1 Guidelines/Technical Justifications

Feedwater chemistry guidelines for power operation are given in Table 6-5. Chemistry guidelines for condensate samples are given in Table 6-6. For normal operation, these values represent limits below which little impurity-related corrosion of steam generator or turbines has been noted by the industry. Out-of-guideline conditions should be corrected to normal values within the time specified. Higher water quality should be maintained whenever possible.

Table 6-5
Once-Through Steam Generator Power Operation (≥15% Reactor Power)
Feedwater Sample

Table 6-6
Once-Through Steam Generator Power Operation (>15% Reactor Power)
Condensate Sample

6.5.4.2 Parameter Justifications

6.5.4.3 Corrective Action Guidelines – Power Operation

After verification that a parameter is out-of-guidelines, the following corrective actions should be considered:

6.6 References

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DATA: COLLECTION, EVALUATION, AND MANAGEMENT

7.1 Introduction

Table 7-1
Continuous Instrumentation Suggestions for Recirculating Steam Generators

7.2 QA/QC Considerations

7.2.1 Basis for Generating Chemistry Data of Known Quality

7.2.2 Data Management

7.2.3 QC Considerations for Secondary Chemistry Control

7.3 Sampling Considerations

7.3.1 General Considerations

7.3.2 Special Sampling Considerations

Figure 7-2
Example of Feedwater Sample Line Configuration for Metal Oxide Sampling

Figure 7-4
Example of a Sample Tee Configuration

Table 7-3
Example Calculation of Oxygen Reduction in a Feedwater Sample Line

7.3.3 Sampling for Lead

7.4 Data Collection

7.5 Data Evaluation Tools

7.5.1 Introduction

7.5.2 EPRI chemWORKS™ Software

7.5.3 Calculated Cation Conductivity

7.5.4 Steam Generator Corrosion Evaluations

7.5.4.1 Source Term Evaluation

Table 7-5
Typical Source and Removal Terms in PWR Secondary Systems

Table 7-6
Source and Removal Term Percentages

7.5.4.2 Source Term Contribution from Total Organic Carbon

7.5.4.3 Integrated Exposure Evaluation (for Recirculating Steam Generators)

*7.5.4.3.1 Integrated Exposure Method A: (ppb*days)*

Figure 7-5
Spreadsheet Used to Calculate IE by Simple Integration Method

Figure 7-6
Sample Sodium IE Calculation for Plant with High Impurity Exposures During Startup

Figure 7-7
Plant Exposure at Normal Operation vs. Reference Plant Exposure

7.5.4.3.2 Integrated Exposure Method B: Tube Exposure Factor

Figure 7-8
Three Cases with Similar Cumulative Mass Accumulation Over the Cycle Length

Figure 7-9
Relative Tube Surface Area Wetted for Three Different Cases where Cumulative Mass Accumulation at the End of the Cycle is the Same

Figure 7-10
Drilled Hole Crevice Geometry

Figure 7-11
Relationship between Surface Area Wetted vs. Volume Filled for an Eccentric Crevice

The spreadsheet used to calculate the tube exposure factors is also easy to setup.

Figure 7-13 depicts a sample spreadsheet.

Figure 7-12
Relative Tube Exposure Factor Illustrating Differences In Exposure for Cases where Total Cumulative Mass Accumulation Over the Cycle Length is the Same

Figure 7-13
Sample Spreadsheet Used to Calculate Tube Exposure Factors

Figure 7-14
Example Relative Tube Exposure Factor for an Actual Operating Cycle Showing the Effect of the Startup Transient

7.5.4.3.3 Integrated Exposure Method C: CREV-SIM

7.5.4.4 Hideout Return Evaluations

7.5.4.6 Sludge Analysis and Monitoring

7.6.2 Integrated Corrosion Product Loading

7.7.4 Steam Generator Corrosion

7.7.5 System/Component Observations

7.7.7 Process Instrument Performance and Reliability

7.7.8 Hideout Return

7.8 References

A
INTEGRATED EXPOSURE EVALUATIONS

A.1 Introduction

This appendix was created to demonstrate how some plants use integrated exposure in practice. Three plant documents (or summaries of plant documents) are presented, which describe different methodologies for use of integrated exposure.

A.2 Integrated Exposure Example 1

A.2.1 PWR Secondary Chemistry Operating Guideline

A.2.1.1 Introduction

A.2.1.2 Purpose

A.2.1.3 Operating Philosophy.

A.2.1.4 Basis

A.2.1.5 Operating Methodology

A.3 Integrated Exposure Example 2

A.3.1 Utilization of Integrated Exposure Limits to Control Molar Ratio

A.4 Integrated Exposure Example 3

A.5 References

B
PWR STEAM CHEMISTRY CONSIDERATIONS

B.1 Introduction

B.2 PWR Steam Chemistry Considerations

B.2.1 Introduction to Paper

This paper reviews the key issues associated with steam chemistry in PWR's. Over the past several years, EPRI and other international organizations have sponsored a research program focused on steam chemistry within power plant steam cycles.

B.2.2 Recommendations

B.2.3 Discussion

B.2.4 Deposition Processes in Turbines

Figure B-1
Location of Salt Concentration in LP Turbines

B.2.5 Steam Chemistry Guidelines

Table B-1
Reheat Steam Limits in Drum Units

B.2.5.1 Acceptability of this Approach to Setting PWR Guidelines

B.2.5.2 Alternative Approach

Figure B-2
Steam Expansion Path for Fossil and Nuclear Steam Cycles

B.3 References

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About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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