



NUCLEAR ENERGY INSTITUTE

**Alex Marion**  
DIRECTOR, ENGINEERING  
NUCLEAR GENERATION DIVISION

October 10, 2003

Dr. Brian W. Sheron  
Associate Director for Project Licensing and Technical Analysis  
Office of Nuclear Reactor Regulation  
U. S. Nuclear Regulatory Commission  
Mail Stop O5-E7  
Washington, DC 20555

**SUBJECT:** Industry Steam Generator Management Project -- New Guidance

**PROJECT NUMBER:** 689

Dear Dr. Sheron:

The Steam Generator Management Project (SGMP) has issued revision 5 to its Pressurized Water Reactor Primary Water Chemistry Guidelines. Copies of this document are enclosed for your information. Your endorsement of this material is not requested.

The guidelines in Enclosure 1 contain proprietary information that is supported by the signed affidavit in Enclosure 2. The affidavit sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the consideration listed in paragraph (b)(4) of Section 2.790 of the Commission's regulations. Accordingly, we respectfully request that the information, which is proprietary to EPRI, be withheld from public disclosure in accordance with 10 CFR 2.790. Copies of the non-proprietary version of the Primary Water Chemistry Guidelines are included in Enclosure 3.

If there are any questions on these matters, please contact me (202-739-8080 or email [am@nei.org](mailto:am@nei.org)) or Jim Riley (202-739-8137 or [jhr@nei.org](mailto:jhr@nei.org)).

Sincerely,

A handwritten signature in black ink that reads 'Alex Marion'.

Alex Marion

Enclosures

c: Ms. Louise Lund, NRC (w/o enclosure)  
Mr. Emmett Murphy, NRC (w/o enclosure)  
Mr. Ken Karwoski, NRC (w/o enclosure)  
Mr. Brian Benney, NRC (w/ enclosure)



Enclosure 2

**PWR Primary Water Chemistry Guidelines  
Revision 5**

**Proprietary Affidavit**

October 6, 2003

Document Control Clerk  
U.S. Nuclear Regulatory Commission  
OWN 11555 Rockville Pike  
Washington DC, 20555

Subject: "PWR Primary Water Chemistry Guidelines: Volumes 1 and 2, Revision 5" FINAL EPRI  
Report 1002884, September 2003.

Gentlemen:

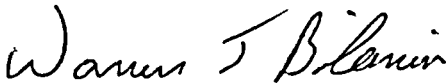
This is a request under 10CFR2.790(a)(4) that the NRC withhold from public disclosure the information identified in the enclosed affidavit consisting of EPRI owned Proprietary Information identified above (the "Report"). Copies of the Report and the affidavit in support of this request are enclosed.

EPRI desires to disclose the Report in confidence to the NRC as a means of exchanging information in support of generic regulatory improvements relating to NEI 97-06, "Steam Generator Program Guidelines." Further, EPRI welcomes any discussion with the NRC regarding the Report that the NRC desires to conduct.

The Report is for the NRC's internal use and may be used only for the purposes for which it is disclosed by EPRI. The report should not be otherwise used or disclosed to any person outside the NRC without prior written permission from EPRI.

If you have any questions about the legal aspects of this request for withholding, please do not hesitate to contact me at (650) 855-2340. Questions on the contents of the Report should be directed to James M. Benson of EPRI at (650) 855-2146.

Sincerely,



Warren J. Bilanin  
Director, Nuclear Power Sector

Enclosures (1)

Cc: Licensing  
Jim Riley / NEI

## AFFIDAVIT

RE: "PWR Primary Water Chemistry Guidelines: Volumes 1 and 2, Revision 5" FINAL EPRI Report 1002884, September 2003.

I, WARREN BILANIN, being duly sworn, depose and state as follows:

I am a Director at the Electric Power Research Institute ("EPRI") and I have been specifically delegated responsibility for the report listed above that is sought under this affidavit to be withheld (the "Report") and authorized to apply for their withholding on behalf of EPRI. This affidavit is submitted to the Nuclear Regulatory Commission ("NRC") pursuant to 10 CFR 2.790 (a)(4) based on the fact that the Report consists of trade secrets of EPRI and that the NRC will receive the Report from EPRI under privilege and in confidence.

The basis for withholding such Report from the public is set forth below:

(i) The Report has been held in confidence by EPRI, its owner. All those accepting copies of the Report must agree to preserve the confidentiality of the Report.

(ii) The Report is a type customarily held in confidence by EPRI and there is a rational basis therefor. The Report is a type, which EPRI considers as a trade secret(s) and is held in confidence by EPRI because to disclose it would prevent EPRI from licensing the Report at fees, which would allow EPRI to recover its investment. If consultants and/or other businesses providing services in the electric/nuclear power industry were able to publicly obtain the Report, they would be able to use it commercially for profit and avoid spending the large amount of money that EPRI was required to spend in preparation of the Report. The rational basis that EPRI has for classifying this/these Report(s) as a trade secrets is justified by the Uniform Trade Secrets Act, which California adopted in 1984 and which has been adopted by over twenty states. The Uniform Trade Secrets Act defines a "trade secret" as follows:

"Trade secret" means information, including a formula, pattern, compilation, program, device, method, technique, or process, that:

(1) Derives independent economic value, actual or potential, from not being generally known to the public or to other persons who can obtain economic value from its disclosure or use; and

(2) Is the subject of efforts that are reasonable under the circumstances to maintain its secrecy.

(iii) The Report will be transmitted to the NRC in confidence.

(iv) The Report is not available in public sources. EPRI developed the Report only after making a determination that the Report was not available from public sources. It required a large expenditure of dollars for EPRI to develop the Report. In addition, EPRI was required to use a large amount of time of EPRI employees. The money spent, plus the value of EPRI's staff time in preparing the Report, show that the Report is highly valuable to EPRI. Finally, the Report was developed only after a long period of effort of at least several months.

(v) A public disclosure of the Report would be highly likely to cause substantial harm to EPRI's competitive position and the ability of EPRI to license the Report both domestically and internationally. The Report can only be acquired and/or duplicated by others using an equivalent investment of time and effort.

I have read the foregoing and the matters stated therein are true and correct to the best of my knowledge, information and belief. I make this affidavit under penalty of perjury under the laws of the United States of America and under the laws of the State of California.

Executed at 3412 Hillview Avenue, Palo Alto, being the premises and place of business of the Electric Power Research Institute:

October 6, 2003



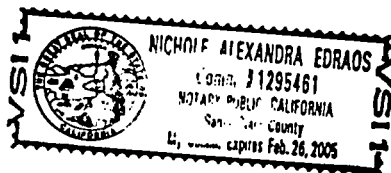
Warren J. Bilanin

Subscribed and sworn before me this day:                      October 6, 2003



Nicole Alexandra Edraos, Notary Republic

October 6, 2003



Enclosure 3

**PWR Primary Water Chemistry Guidelines  
Revision 5**

**Non - Proprietary Version**

# **Pressurized Water Reactor Primary Water Chemistry Guidelines**

Volume 1, Revision 5

1002884

Final Report, September 2003

**NON-PROPRIETARY VERSION**

EPRI Project Managers  
P. Frattini  
K. Fruzzetti

# **Pressurized Water Reactor Primary Water Chemistry Guidelines**

Volume 1, Revision 5

**1002884**

Final Report, September 2003

**NON-PROPRIETARY VERSION**

EPRI Project Managers  
P. Frattini  
K. Fruzzetti



## **DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES**

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

**PWR Primary Water Chemistry Guidelines Committee**

## **ORDERING INFORMATION**

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2003 Electric Power Research Institute, Inc. All rights reserved.

# CITATIONS

This report was prepared by

PWR Primary Water Chemistry Guidelines Committee

<b>AECL</b> J. Sawicki	<b>First Energy</b> V. Linnenbom, S. Slosnerick	<b>Pacific Gas &amp; Electric</b> C. Bowler
<b>Ameren UE</b> G. Gary, E. Olson, J. Small	<b>Florida Power &amp; Light</b> C. Connelly	<b>Progress Energy</b> N. Bach, P. Cross, E. Meyer, R. Thompson
<b>American Electric Power</b> K. Haglund, D. Kozin	<b>Framatome ANP</b> W. Allmon, L. Lamanna	<b>PSE&amp;G Nuclear LLC</b> J. Riddle
<b>AmerGen Energy</b> B. Walton	<b>GEBCO Engineering, Inc.</b> G. Brobst	<b>Ringhals</b> P.-O. Andersson, B. Bengtsson
<b>Arizona Public Service</b> J. Santi	<b>INPO</b> R. Schirmer	<b>Rochester Gas and Electric</b> G. Jones
<b>Babcock &amp; Wilcox</b> P. King	<b>iSagacity</b> J. Bates	<b>South Carolina Electric &amp; Gas</b> F. Bacon
<b>British Energy</b> J. C. Bates, K. Garbett, Consultant	<b>Laborelec</b> E. Girasa, C. Laire	<b>Southern California Edison</b> J. Muniga
<b>Constellation Energy</b> E. Eshelman	<b>NMC</b> C. Jones, S. Lappegaard, J. McElrath	<b>Southern Nuclear</b> F. Hundley, D. Rickertsen
<b>Dominion Engineering</b> J. Gorman	<b>NPP Krsko</b> K. Fink	<b>STPNOC</b> D. Bryant, R. Ragsdale
<b>Dominion Resources</b> E. Frese	<b>N. Atlantic Energy Serv. Co.</b> R. Litman, L. Michaud, G. Miller	<b>TXU Energy</b> K. Cooper, B. Fellers, L. Wilson
<b>Duke Energy</b> K. Johnson	<b>NWT Corp.</b> S. Sawochka	<b>TVA</b> D. Adams, D. Bodine
<b>Electricité de France</b> J.-L. Belzic	<b>Ontario Power Generation</b> K. Bagli	<b>Westinghouse</b> A. Byers, J. Kormuth, S. Lurie, N. Vitale
<b>Entergy</b> G. Dolese, D. Wilson	<b>OPPD</b> T. Dukarski	<b>WCNOC</b> J. Kuras, J. Truelove
<b>Exelon</b> R. Claes		

## ELECTRIC POWER RESEARCH INSTITUTE

P. Frattini, Chairman; J. Blok, B. Cheng, J. Deshon, K. Fruzzetti, J. Hickling, H. Ocken, R. Pathania, C. Wood

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 Primary Water Chemistry Guidelines: Volume 1, Revision 5, EPRI, Palo Alto, CA: 2003. 1002884.*

# REPORT SUMMARY

---

State-of-the art water chemistry programs help ensure the continued integrity of reactor coolant system (RCS) materials of construction and fuel cladding, ensure satisfactory core performance, and support the industry trend toward reduced radiation fields. These revised *PWR Primary Water Chemistry Guidelines*, prepared by a committee of industry experts, reflect the recent field and laboratory data on primary coolant system corrosion and performance issues. Volume 1 covers operating chemistry and Volume 2 covers startup and shutdown chemistry.

## Background

EPRI periodically updates the PWR water chemistry guidelines as new information becomes available and as required by NEI 97-06, Steam Generator Program Guidelines. The last revision of these Guidelines identified an optimum primary water chemistry program based on then-current understanding of research and field information. This revision provides further details with regard to primary water stress corrosion cracking (PWSCC), fuel integrity, and shutdown dose rates.

## Objective

To update the *PWR Primary Water Chemistry Guidelines, Revision 4*, published in 1999.

## Approach

A committee of industry experts, including utility specialists, nuclear steam supply system and fuel vendor representatives, Institute of Nuclear Power Operations representatives, consultants, and EPRI staff, collaborated in reviewing the available data on primary water chemistry, reactor water coolant system materials issues, fuel integrity and performance issues, and radiation dose rate issues. From these data, the committee generated water chemistry guidelines that all PWR nuclear plants should adopt. 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 operation.

## Results

Revision 5 of the *PWR Primary Water Chemistry Guidelines*, which provides recommendations for PWR primary systems of all manufacture and design, includes the following updates:

The Guidelines continue to emphasize plant-specific optimization of water chemistry to address individual plant circumstances. The committee revised guidance with regard to optimization to reflect industry experience gained since the publication of Revision 4. This revision continues to distinguish between prescriptive requirements and non-prescriptive guidance.

The revised Sections 2 and 3 of Volume 1 address the latest information on PWSCC of RCS materials, fuel cladding integrity and core performance, and radiation field control. The guidelines emphasize optimization of pH control programs with regard to maintaining system integrity, minimizing the potential for axial offset anomaly and excessive fuel deposits, use of zinc additions to minimize shutdown dose rates and mitigate PWSCC concerns, and ensuring that pH programs do not have adverse impacts on PWSCC or fuel cladding integrity.

The committee reviewed and revised shutdown and startup chemistry coverage in Volume 2 to reflect industry experience gained in this area since issuance of Revision 4. In particular, the technical basis for corrosion product transport and activity transport control were updated with the significant results of studies of fuel deposits from cores with significant local assembly steaming or core-wide high duty commensurate with axial offset anomaly.

The committee also updated or added several appendices to Volumes 1 and 2. These include new sections on RCS sampling, ultrasonic fuel cleaning technology, radiochemistry, definition of a high duty core index, and mid-cycle shutdown/startup decision logic.

### **EPRI Perspective**

This fifth revision of the *PWR Primary Water Chemistry Guidelines*, endorsed by the utility executives of the EPRI Steam Generator Management Project, represents another step in the continuing use of proactive chemistry programs to limit or control degradation of steam generator tubes and other structural parts. This revision documents the increased consideration of state-of-the art water chemistry programs to help ensure the continued integrity of reactor coolant system (RCS) materials of construction and fuel cladding, ensure satisfactory core performance, and support the industry trend toward reduced radiation fields. These revised *PWR Primary Water Chemistry Guidelines* reflect the recent field and laboratory data on primary coolant system corrosion and performance issues, which PWR operators can use to update their primary water chemistry programs.

### **Keywords**

PWRs

Water chemistry

Primary water stress corrosion cracking

Guidelines

Reactor coolant system

## **ABSTRACT**

---

Ensuring continued integrity of RCS materials of construction and fuel cladding and maintaining the industry trend toward reduced radiation fields requires continued optimization of reactor coolant chemistry. Optimization of coolant chemistry to meet site-specific demands becomes increasingly important in light of the movement toward extended fuel cycles, higher duty cores, increasingly stringent dose rate control, decreased refueling outage duration, and reduced operating costs. This document is the sixth in a series of industry guidelines on PWR primary water chemistry. Like each of the others in the series, it provides a template for development of a plant-specific water chemistry program.

## EPRI FOREWORD

---

Chemistry optimization of pressurized water reactor (PWR) primary systems in recent times has been complicated by the demands of longer fuel cycles (i.e., higher initial boron concentrations), increased fuel duty (more subcooled boiling) and material/fuel corrosion concerns. Current utility concerns focus on minimizing costs without sacrificing materials integrity or safety. These *Guidelines* provide a template for a responsive chemistry program for PWR primary systems and the technical bases/supporting information for the program. It is the fifth revision of the *Guidelines* and considers the most recent operating experience and laboratory data. The *Guidelines* will be of interest to plant chemists, plant managers, chemical engineers, and engineering managers within utilities owning PWRs.

The *Guidelines* were prepared by a committee of experienced industry personnel through an effort sponsored by EPRI. Participation was obtained from chemistry, materials, steam generator, and fuels experts to ensure the *Guidelines* present chemistry parameters that are optimum for each set of operating and material conditions. Each EPRI-member utility operating a PWR participated in generation or review of these *Guidelines*. Therefore, this document serves as an industry consensus for PWR primary water chemistry control. In essence, it is a report from industry specialists to the utilities documenting an optimized water chemistry program.

Special acknowledgment is given to the following organizations for submitting first-hand experience through committee participation:

- Ameren UE
- American Electric Power
- AmerGen Energy
- Arizona Public Service
- Atomic Energy of Canada, Ltd.
- Babcock & Wilcox
- British Energy
- Constellation Energy
- Dominion Resources
- Duke Energy
- Electricité de France
- Entergy
- Exelon
- First Energy

- 
- Florida Power & Light
  - Framatome ANP
  - INPO
  - Laborelec (Belgium)
  - NPP Krsko
  - Nuclear Management Corporation (NMC)
  - Omaha Public Power District
  - Ontario Power Generation
  - Pacific Gas & Electric Company
  - Progress Energy
  - Public Service Electric & Gas
  - Ringhals (Sweden)
  - Rochester Gas and Electric
  - South Carolina Electric & Gas
  - Southern California Edison
  - Southern Nuclear Operating Co.
  - South Texas Project Nuclear Operating Company
  - Tennessee Valley Authority
  - TXU Energy
  - Westinghouse Electric
  - Wolf Creek Nuclear Operating Corp.

This committee was significantly assisted in its work by J. Gorman of Dominion Engineering; G. Brobst of GEBCO Engineering; J. Bates of iSagacity; K. Garbett, consultant; H. Sims of AEA Technology; R. Litman, consultant; S. Sawochka of NWT Corporation. In addition, the Committee would like to acknowledge the support and input of fuel specialists from EPRI-member utilities.

This document is intended to be a set of guidelines which describe an effective, state-of-the-art program from which a utility can develop an optimized program for their plant. The philosophy embodied in this document has generic applicability, but can be adapted to the particular conditions of the utility and the site. The detailed guidelines presented in Sections 3 and 4 of this volume and of Volume 2 on startup and shutdown chemistry comprise a program that should serve as a model for the development of site-specific chemistry plans.

Relative to Rev. 4 of these *Guidelines*, the major changes in Volume 1 of this document are as follows:







---

Paul L. Frattini, Chairman  
PWR Primary Water Chemistry Guidelines Revision Committee  
EPRI Nuclear Power Group  
March 2003

## ACRONYMS

---

AOA	Axial offset anomaly
BAST	Boric acid storage tank
BOC	Beginning of cycle
BRS	Boron recovery system.
BTRS	Boron thermal regeneration system
BWR	Boiling water reactor
CVCS	Chemical and volume control system. The term makeup system (MU) is used at some plants for the same system.
DEI	Dose equivalent iodine-131
DF	Decontamination factor
DHC	Debye-Huckel limiting slope
DRP	Discrete radioactive particle
$\bar{E}$	E-bar, average disintegration energy
EBA	Enriched boric acid
ECP	Electrochemical potential
EPRI	Electric Power Research Institute
EOC	End of cycle
HDCI	High duty core index
HUT	Holdup tank.
IGSCC	Intergranular stress corrosion cracking
INPO	Institute of Nuclear Power Operations
LTCP	Low temperature crack propagation
LTOP	Low temperature overpressure
NEI	Nuclear Energy Institute
NSSS	Nuclear steam system supplier
NTU	Nephelometric turbidity units
PRT	Pressurized relief tank
PWR	Pressurized water reactor
PWSCC	Primary water stress corrosion cracking
RCP	Reactor coolant pump
RCS	Reactor coolant system. For purposes of these <i>Guidelines</i> , the RCS includes the pressurizer.
RFO	Refueling outage
RHR	Residual heat removal system. The terms decay heat (DH) system and shutdown cooling (SDC) system are used at some plants for the same system.
RWST	Refueling water storage tank. The term borated water storage tank (BWST) is used at some plants for the same tank.
SCC	Stress corrosion cracking

---

SFP	Spent fuel pool system. The term spent fuel cooling (SFC) system is used at some plants for the same system.
STP	Standard temperature and pressure
TOC	Total organic carbon
TSS	Total suspended solids
VCT	Volume control tank. The term makeup tank (MUT) is used at some plants for the same tank.

# CONTENTS

---

<b>1 INTRODUCTION AND MANAGEMENT RESPONSIBILITIES .....</b>	<b>1-1</b>
1.1 Introduction .....	1-1
1.2 Generic Management Considerations.....	1-3
1.3 Communication and Training .....	1-4
1.4 Outage Planning and Coordination .....	1-4
<b>2 TECHNICAL BASIS FOR THE NEED TO CONTROL THE COOLANT CHEMISTRY IN PWRS.....</b>	<b>2-1</b>
2.1 Introduction .....	2-1
2.2 Discussion of Chemistry Regimes.....	2-2
2.3 Materials Integrity in the Reactor Coolant System .....	2-6
2.3.1 Corrosion Modes of Structural Materials .....	2-6
2.3.2 Effects of Chemistry Parameters .....	2-8
2.3.2.1 PWSCC Mechanisms .....	2-8
2.3.2.2 Dissolved Oxygen.....	2-10
2.3.2.3 Dissolved Hydrogen – Effects at Operating Temperatures.....	2-10
2.3.2.4 Dissolved Hydrogen – Low Temperature Considerations.....	2-17
2.3.2.5 pH .....	2-18
2.3.2.6 Lithium .....	2-21
2.3.2.7 Analytical Evaluation of Effect of Lithium-pH History on PWSCC Susceptibility .....	2-23
2.3.2.8 Plant Experience Regarding Effects of Lithium and pH on PWSCC.....	2-24
2.3.2.9 Chloride .....	2-27
2.3.2.10 Fluoride.....	2-27
2.3.2.11 Sulfate.....	2-27
2.3.2.12 Organics .....	2-28
2.3.2.13 Zinc .....	2-28
2.4 Fuel Integrity Considerations.....	2-30

2.4.1 Chemistry Effects on Fuel Reliability .....	2-30
2.4.1.1 Cladding Corrosion .....	2-31
2.4.1.2 Fuel Crud Deposition .....	2-34
2.4.2 Effects of Chemistry Parameters .....	2-35
2.4.2.1 Dissolved Oxygen .....	2-35
2.4.2.2 Fluoride .....	2-36
2.4.2.3 Aluminum, Calcium, Magnesium, and Silica .....	2-36
2.4.2.4 Suspended Solids .....	2-39
2.4.2.5 pH .....	2-39
2.4.2.6 Lithium .....	2-40
2.4.2.7 Zinc .....	2-42
2.4.3 PWR Axial Offset Anomaly .....	2-44
2.5 Radiation Field Control .....	2-46
2.5.1 Sources of Radiation Fields .....	2-46
2.5.2 Effects of Chemistry Parameters .....	2-47
2.5.2.1 Corrosion Product Release .....	2-48
2.5.2.2 Particulate Transport .....	2-48
2.5.2.3 Soluble Transport .....	2-49
2.5.2.4 Verification Tests and Plant Experience .....	2-51
2.5.2.5 Plant Data .....	2-52
	..2-52
	..2-53
	..2-54
	..2-54
2.5.2.6 Zinc .....	2-55
2.5.3 Summary .....	2-57
<b>3 POWER OPERATION CHEMISTRY CONTROL RECOMMENDATIONS.....</b>	<b>3-1</b>
3.1 Introduction .....	3-1
3.2 Reactor Coolant System (RCS) pH Optimization .....	3-1
3.2.1 Operating Recommendations .....	3-1
3.2.2 Transition to Constant pH Operation .....	3-9
3.3 Control and Diagnostic Parameters .....	3-11
3.4 Guideline Recommendations .....	3-11
3.4.1 Goals .....	3-11

---

3.4.2 Corrective Actions .....	3-12
3.5 Definitions of Terms Used in the Guidelines .....	3-12
3.5.1 Plant Status .....	3-12
3.5.2 Action Levels .....	3-12
3.5.2.1 Action Level 1 .....	3-13
3.5.2.2 Action Level 2 .....	3-13
3.5.2.3 Action Level 3 .....	3-14
3.6 Guideline Values for Chemistry Parameters During Power Operation.....	3-14
3.6.1 Reactor Coolant System Guidelines.....	3-14
3.6.2 Special Considerations.....	3-18
3.6.2.1 Axial Offset Anomaly.....	3-18
3.6.2.2 Zinc Addition .....	3-19
3.6.2.3 Extended Fuel Cycles .....	3-19
3.6.2.4 Operation With Unusual Levels of Lithium.....	3-19
3.6.2.5 Chemistry Program Modification.....	3-20
3.6.3 Primary System Makeup Water.....	3-21
3.7 Control and Diagnostic Parameters, Frequencies, and Limits for Startup Chemistry .....	3-21
<b>4 METHODOLOGY FOR PLANT-SPECIFIC OPTIMIZATION .....</b>	<b>4-1</b>
4.1 Introduction .....	4-1
4.2 Primary Water Chemistry Variables and Options.....	4-2
4.2.1 Program Objectives .....	4-2
4.2.2 Parameters Impacting Structural Integrity .....	4-2
4.2.2.1 Chloride/Fluoride/Sulfate .....	4-3
4.2.2.2 Dissolved Oxygen Control .....	4-3
4.2.2.3 Hydrogen .....	4-4
4.2.2.4 pH <sub>T</sub> (Lithium Control Parameter).....	4-4
4.2.2.5 Zinc .....	4-5
4.2.3 Parameters With Negligible Impact on Structural Integrity .....	4-5
4.2.3.1 Silica .....	4-5
4.2.3.2 Suspended Solids.....	4-6
4.2.4 Chemistry Control During Shutdowns and Startups .....	4-6
4.2.4.1 Shutdown Chemistry Program.....	4-6
4.2.4.2 Startup Chemistry Program .....	4-6

4.3 Optimization Methodology.....	4-6
4.3.1 Optimization Process.....	4-6
4.3.2 NEI SG Initiative Checklist.....	4-7
<b>5 REFERENCES .....</b>	<b>5-1</b>
<b>A CALCULATION OF PHT AND DATA EVALUATION METHODOLOGIES .....</b>	<b>A-1</b>
1.0 Calculation of pH <sub>T</sub> .....	A-1
.....	A-1
2.0 Low Temperature pH, Boron, Lithium Calculations and Data .....	A-9
.....	A-10
.....	A-11
3.0 .....	A-14
.....	A-15
.....	A-16
4.0 Verification and Validation of the EPRI chemWORKS™ Primary System pH .....	A-18
5.0 Temperature and Pressure Dependence of pH .....	A-19
.....	A-20
.....	A-21
6.0 Monitoring for Fuel Reliability.....	A-22
7.0 Primary-to-Secondary Leak Monitoring.....	A-22
8.0 References.....	A-23
<b>B CHEMISTRY CONTROL OF SUPPORTING SYSTEMS.....</b>	<b>B-1</b>
1.0 Introduction .....	B-1
2.0 Letdown Purification System.....	B-1
2.1 System Description.....	B-1
2.2 Selection Criteria for Purification Filters and Ion Exchange Resins .....	B-2
2.3 Performance Monitoring .....	B-2
2.4 Selected Industry Experiences .....	B-5
2.4.1 Resin Intrusions .....	B-5
2.4.2 Chloride Elution.....	B-5
2.4.3 Leachable Impurities.....	B-5
2.4.4 Boron/Power Excursions.....	B-5



---

2.4.5	Lithium Excursions/Power Effects.....	B-6
2.4.6	Shutdown Sulfate Increases .....	B-6
2.4.7	Makeup Water Contamination .....	B-6
3.0	Volume Control Tank.....	B-7
3.1	System Description.....	B-7
3.2	Chemistry Control and Technical Basis.....	B-7
3.3	Selected Industry Experiences .....	B-9
3.3.1	VCT Vapor Space Composition .....	B-9
4.0	Pressurizer .....	B-9
4.1	System Description.....	B-9
4.2	Chemistry Control and Technical Basis.....	B-10
4.3	Industry Experience.....	B-10
4.3.1	Corrosion Observations .....	B-10
4.3.2	RCS Hydrogen Control .....	B-11
4.3.3	Chloride Contamination .....	B-11
5.0	Boric Acid Storage.....	B-11
5.1	System Description.....	B-11
5.2	Chemistry Control and Technical Basis.....	B-12
5.3	Industry Experience.....	B-13
5.3.1	Silica Transport.....	B-13
5.3.2	Boric Acid Crystallization .....	B-13
5.3.3	Chloride Contamination .....	B-14
5.3.4	Magnesium Contamination .....	B-14
5.3.5	Sulfate Contamination.....	B-14
6.0	Refueling Water Storage Tank.....	B-14
6.1	System Description.....	B-14
6.2	Chemistry Control and Technical Basis.....	B-14
6.3	Industry Experience.....	B-16
6.3.1	Reactor Water Clarity.....	B-16
6.3.2	Resin Contamination.....	B-16
6.3.3	Silica Control.....	B-16
6.3.4	Chloride / Fluoride Contamination Due to Freon Intrusion.....	B-16
7.0	Spent Fuel Pool Cooling and Cleanup System .....	B-16
7.1	System Description.....	B-16

7.2 Chemistry Controls and Technical Basis.....	B-17
7.3 Industry Experience.....	B-19
7.3.1 Failure of Bundle Top Nozzles.....	B-19
7.3.2 Silica Control.....	B-19
8.0 References.....	B-19
<b>C STATUS OF ENRICHED BORIC ACID (EBA) APPLICATION.....</b>	<b>C-1</b>
1.0 Introduction .....	C-1
2.0 Summary of EPRI Studies.....	C-1
3.0 Plant Demonstrations of EBA.....	C-2
4.0 References .....	C-3
<b>D AOA AND ULTRASONIC FUEL CLEANING .....</b>	<b>D-1</b>
1.0 Background .....	D-1
2.0 Ultrasonic Fuel Cleaning Technology.....	D-1
3.0 System Description .....	D-2
4.0 Fuel Cleaning Efficacy.....	D-3
5.0 Full-Reload Cleaning Results.....	D-4
6.0 Fuel Cleaning Performance.....	D-4
7.0 Conclusions.....	D-6
8.0 References .....	D-6
<b>E OXYGEN AND HYDROGEN BEHAVIOR IN PWR PRIMARY CIRCUITS .....</b>	<b>E-1</b>
1.0 Summary .....	E-1
2.0 Radiation Chemistry .....	E-1
3.0 Minimum Hydrogen Concentrations at Full Power .....	E-2
4.0 The Effect of Voidage on Minimum Hydrogen Levels .....	E-5
4.1 Metal Ion Chemistry .....	E-7
5.0 Oxygen Ingress .....	E-7
6.0 Startup Deoxygenation.....	E-12
7.0 Spent Fuel Pool.....	E-13
8.0 Conclusions.....	E-13
9.0 References .....	E-14
<b>F SAMPLING CONSIDERATIONS FOR MONITORING RCS CORROSION PRODUCTS.....</b>	<b>F-1</b>

1.0 Background on RCS Sampling Technology .....	F-1
2.0 Existing Sampling Practices .....	F-3
3.0 Continuous Corrosion Product Sampling .....	F-4
3.1 Background .....	F-4
3.2 Continuous Sampling and Analysis Methods .....	F-10
.....	F-10
.....	F-14
3.3 Conclusions .....	F-15
4.0 Augmented Reactor Coolant Corrosion Product Sampling at .....	F-16
5.0 References .....	F-20

## **G REACTOR COOLANT RADIONUCLIDES..... G-1**

1.0 Formation of Radionuclides in the RCS .....	G-1
1.1 Radionuclides Formed by Fission .....	G-8
.....	G-9
.....	G-10
.....	G-13
1.2 Radionuclides Formed by Activation .....	G-14
.....	G-15
.....	G-15
.....	G-16
.....	G-16
.....	G-19
2.0 Measurement of Radionuclides in the Reactor Coolant System.....	G-20
2.1 Examples of Measurement of Radionuclides by Adjusting Sample/Counting Parameters .....	G-20
2.2 Identifying Unknown Gamma Ray Peaks .....	G-22
3.0 Expected Concentrations and Trends of RCS Radionuclides .....	G-28
3.1 Fission Products .....	G-28
3.2 Activation Product Trends .....	G-32
4.0 References .....	G-35

## **H DEFINITION OF HIGH DUTY CORE: A MEANS FOR EVALUATING THE PROPENSITY TO DEPOSIT CRUD ON FUEL ASSEMBLIES..... H-1**

1.0 Background .....	H-1
----------------------	-----

---

2.0 Definition .....	H-1
3.0 Methodology.....	H-2
4.0 Case Example .....	H-2
5.0 High Duty – Medium Duty – Low Duty .....	H-3
6.0 References .....	H-4

## LIST OF FIGURES

Figure 2-1 Schematic of the Problems with Optimizing RCS pH Control.....	2-2
Figure 2-2 Schematic of Coordinated Chemistry Regime (at 300°C) .....	2-4
Figure 2-3 Schematic of Elevated Chemistry Regime (at 300°C).....	2-4
Figure 2-4 Schematic of Modified Chemistry (at 300°C).....	2-5
Figure 2-5 Schematic of Coordinated Chemistry at pH <sub>T</sub> 7.1 Consistent with Lithium Below 3.5 ppm (at 300°C) .....	2-5
Figure 2-6 The Effects of Oxygen and Chloride on the Stress Corrosion Cracking of Austenitic Stainless Steel in High Temperature Water.....	2-7
Figure 2-7 Effect of Hydrogen Concentration on Time to PWSCC Crack Initiation at 330°C (626°F).....	2-13
Figure 2-8 Analysis of selected single-variable experiments and comparison with MRP- 68 model .....	2-14
Figure 2-9 The Effects of Hydrogen Concentration and Temperature on Ni/NiO Phase Stability and Peak Crack Growth Rate for PWSCC in Alloy 600 .....	2-15
Figure 2-10 PWSCC Crack Growth Rate Variation with Hydrogen Concentration at 320°C (608°F) and 360°C (680°F) .....	2-16
Figure 2-11 Variation of Crack Growth Rate in Two Heats of Alloy 600 at 325°C (617°F) vs. pH <sub>T</sub> .....	2-19
Figure 2-12 Variation of Crack Growth Rate in Two Heats of Alloy 600 at 325°C (617°F) vs. Lithium Concentration.....	2-20
Figure 2-13 Comparison of WOG Test Results with PWSCC Model and Field Data .....	2-21
Figure 2-14 Effect of Lithium Concentration on Characteristic Life.....	2-22
Figure 2-15 PWSCC Experience during Chemistry Change at Typical EDF Unit (Modified pH <sub>T</sub> 7.0 to Modified pH <sub>T</sub> 7.2) .....	2-25
Figure 2-16 Crack Growths at Roll Transitions in                      Steam Generators .....	2-26
Figure 2-17 Zircaloy Corrosion Versus Core Burn-Up - Industry Experience .....	2-31
Figure 2-18 ZIRLO™ and Zircaloy-4 Cladding Corrosion vs. Fuel Duty Index .....	2-33
Figure 2-19 M5 and Improved Zircaloy-4 Cladding Corrosion vs. Rod Average Burn-up.....	2-33
Figure 2-20 Solubility of Magnesium Silicates at 350°C (662°F).....	2-37
Figure 2-21 Radiation Field Trends in PWRs .....	2-47
Figure 2-22 Variations in Iron Solubility from Core Inlet to Outlet as a Function of pH <sub>T</sub> at the Core Average Coolant Temperature (Boron = 600 ppm, H <sub>2</sub> = 35 cc/kg H <sub>2</sub> O) .....	2-50
Figure 2-23 Variations in Nickel Solubility from Core Inlet to Outlet as a Function of pH <sub>T</sub> at the Core Average Coolant Temperature (B = 600 ppm, H <sub>2</sub> = 35 cc/kg H <sub>2</sub> O) .....	2-51

Figure 2-24 Variation with pH of Average Activities of Co-60 and Co-58 on Steam Generator Tubing at the End of MIT in-Pile Loop Tests.....	2-52
Figure 2-25 Steam Generator Channel Head Dose Rates .....	2-55
Figure 3-1 Schematic Representation of the PWR Primary Chemistry Optimization Problem.....	3-3
Figure 3-2 Transition Chemistry to Elevated pH <sub>T</sub> (>6.9) Example Li/B Programs (plotted at T <sub>ave</sub> =300°C) .....	3-6
Figure 3-3 Constant Elevated pH Chemistry (pH <sub>T</sub> = 7.2) (plotted at T <sub>ave</sub> =300°C (572°F)) .....	3-7
Figure 3-4 Variation of pH Due to Tolerance Band for Lithium as Function of Boron Concentration, for Target pH <sub>300°C</sub> = 7.2 ([Li] at Target Value ± 5% for [Li] ≥ 3.0 ppm, ± 0.15 ppm for 3.0 ppm > [Li] ≥ 1.25 ppm, and ± 12% for [Li] < 1.25 ppm).....	3-9
Figure 5-1 Lithium-Boron Relationships for Various pH at 275°C.....	A-4
Figure A-2 Lithium additions for historical "modified" chemistry control program illustrating difference calculated for pH(T <sub>ave</sub> =310°C) vs. pH(T <sub>ref</sub> =300°C).....	A-20
Figure D-1 Schematic of EPRI's ultrasonic fuel cleaning system .....	D-3
Figure D-2 offset. Cycle 12 (no AOA) and Cycle 11 (with AOA) .....	D-5
Figure E-1 Concentrations of O <sub>2</sub> and H <sub>2</sub> O <sub>2</sub> Around the Main Reactor Loop During Full Power Operation. 25 cc/kg H <sub>2</sub> , 1800 ppm Boron. ....	E-3
Figure E-2 Steady-state O <sub>2</sub> and H <sub>2</sub> O <sub>2</sub> Concentrations at 1800 ppm Boron, Corresponding to the Start of an 18 Month Fuel Cycle (pH(300°C) 6.9).....	E-4
Figure E-3 Steady-state O <sub>2</sub> and H <sub>2</sub> O <sub>2</sub> Concentrations at 0 ppm Boron, Corresponding to the End of an 18 Month Fuel Cycle (pH(300°C) 7.4) .....	E-4
Figure E-4 Concentrations of O <sub>2</sub> and H <sub>2</sub> O <sub>2</sub> Around the Main Reactor Loop. 25cc/kg H <sub>2</sub> , 1800 ppm B, Full Power Operation, Oxygen Ingress from the CVCS. Two Transits Around the Main Circuit are Shown (taken as 56 m long).....	E-10
Figure E-5 Variation of O <sub>2</sub> and H <sub>2</sub> O <sub>2</sub> Concentrations Through the Core for Different Hydrogen Levels, O <sub>2</sub> Ingress, 1 Day After Shut down, 177°C .....	E-11
Figure F-1 Changes in Soluble Nickel and Cobalt Concentrations at due to Changes in Flow Rate .....	F-5
Figure F-2 Changes in Measured Particulate Concentrations at due to Changes in Flow Rate .....	F-6
Figure F-3 Triple Take-off Capillary Sampler.....	F-11
Figure F-4 Capillary Line Sampling Arrangement at .....	F-12
Figure F-5 Schematic Arrangement of the Capillary Line Sample Lines Installed at PWR.....	F-14
Figure F-6 High Temperature Sampler .....	F-17
Figure F-7 High Temperature Filter Schematic.....	F-18
Figure F-8 High Temperature Filer Housing .....	F-19
Figure G-1 Fission Product Curve for Slow-Neutron Fissioning of Uranium-235.....	G-8
Figure G-2 Example of Grid-to-Rod Fretting and RCS Radionuclides at .....	G-11
Figure G-3 Activity Decay Curve.....	G-26
Figure G-4 Noble Gas and Iodine Ratio Changes with a Tight Fuel Defect .....	G-27

---

Figure G-5 Noble Gas and Iodine Concentrations for Tight Fuel Defect .....	G-29
Figure G-6 Noble Gas and Iodine Activities with an Open Fuel Defect .....	G-30
Figure G-7 Noble Gas and Iodine Ratios with an Open Fuel Defect .....	G-31
Figure G-8 Changes in Corrosion Products and Lithium During CRDM Surveillance .....	G-34

## LIST OF TABLES

Table 2-1 Comparison of the Relative Effects of Individual Variables in the MRP-68 Model .....	2-12
Table 2-2 Effect of Primary Water Chemistry on Alloy 600 Crack Growth Rates at 325°C (617°F).....	2-19
Table 3-1 Generic Principles for Optimization of Primary System pH.....	3-4
Table 3-2 Operational Status Modes .....	3-12
Table 3-3 Reactor Coolant System Power Operation Control Parameters (Reactor Critical) .....	3-15
Table 3-4 Reactor Coolant System Power Operation Diagnostic Parameters (Reactor Critical) .....	3-16
Table 3-5 Source Water for Reactor Makeup Diagnostic Parameters – All Modes .....	3-21
Table 3-6 Reactor Coolant System Cold Shutdown Control Parameters (Reactor <250°F (121°C)).....	3-22
Table 3-7 Reactor Coolant System Startup Control Parameters (Reactor Subcritical and >250°F (121°C)) .....	3-22
Table 3-8 Reactor Coolant System Startup Chemistry Diagnostic Parameters (Following Fill-and-Vent to Reactor Critical) .....	3-23
Table 4-1 Chemistry Control Program Approaches .....	4-8
Table A-1 Relation of pH at 275°C to Lithium and Boron Concentrations .....	A-5
Table A-2 Relation of pH at 280°C to Lithium and Boron Concentrations .....	A-5
Table A-3 Relation of pH at 285°C to Lithium and Boron Concentrations .....	A-6
Table A-4 Relation of pH at 290°C to Lithium and Boron Concentrations .....	A-6
Table A-5 Relation of pH at 295°C to Lithium and Boron Concentrations .....	A-7
Table A-6 Relation of pH at 300°C to Lithium and Boron Concentrations .....	A-7
Table A-7 Relation of pH at 305°C to Lithium and Boron Concentrations .....	A-8
Table A-8 Relation of pH at 310°C to Lithium and Boron Concentrations .....	A-8
Table A-9 Relation of pH at 315°C to Lithium and Boron Concentrations .....	A-9
Table A-10 Variables and equations for solving the Li-B system.....	A-11
Table A-11 Constants used for Table A-10 equations .....	A-12
Table A-12 pH of Boric Acid - Lithium Hydroxide Solutions at 25°C.....	A-13
Table A-13 Equivalent Conductance of 25°C .....	A-15
Table A-14 Conductivity of Boric Acid - Lithium Hydroxide Solutions at 25°C.....	A-17
Table B-1 Solubility In Water For Various Gases .....	B-8



---

Table F-1 Corrosion Product Concentrations for Different Reactor Types .....	F-8
Table G-1 Radionuclides Found in the Reactor Coolant System and Potential Sources .....	G-3
Table G-2 Radionuclides Not Identified Directly by Gamma Spectroscopy or Determined by Other Means (Refer to Chart of Nuclides for Half Lives).....	G-6
Table G-3 Theoretical and Actual Iodine Activity Ratios Relative to <sup>131</sup> I (No fuel defects).....	G-9
Table G-4 Gamma Ray Peaks of Nuclides Which Can be Obscured or Misinterpreted .....	G-23
Table H-1 Values of High Duty Core Index for Specific Cycles of Various Plants .....	H-5

# 1

## INTRODUCTION AND MANAGEMENT RESPONSIBILITIES

---

### 1.1 Introduction

The purpose of this document is to provide recommendations on primary chemistry control to continue to maximize the long-term availability of PWR plants. The nuclear power industry has compiled an excellent performance history in maintaining PWR primary system component integrity. In addition, primary water chemistry control can and has been effectively used to control radiation field buildup on ex-core surfaces.

It is important that all levels of utility management understand that operation outside the recommended chemistry limits can increase the probability of reduced unit availability. Such losses may be limited by controlling the magnitude and frequency of abnormal reactor coolant system (RCS) chemistry conditions. A principal goal has been to minimize corrosion of RCS components. Effectively implementing these *Guidelines* will support this goal, thereby maximizing the cumulative availability of the unit. In addition, the US nuclear power industry established a framework for increasing the reliability of steam generators by adopting NEI 97-06, *Steam Generator Program Guidelines*, and has re-affirmed this commitment by adopting Revision 1 of NEI-97-06. This initiative adopted EPRI's Water Chemistry Guidelines, including this document, as the basis for an optimized chemistry program. Specifically, the initiative required that US utilities meet the intent of the *EPRI PWR Primary Water Chemistry Guidelines*.

---

## *Introduction and Management Responsibilities*

## **1.2 Generic Management Considerations**

### **1.3 Communication and Training**

### **1.4 Outage Planning and Coordination**

# 2

## TECHNICAL BASIS FOR THE NEED TO CONTROL THE COOLANT CHEMISTRY IN PWRS

---

### 2.1 Introduction

The purposes of PWR primary coolant chemistry guidelines are:

- To assure primary system pressure boundary integrity,
- To assure fuel-cladding integrity and achievement of design fuel performance, and
- To minimize out-of-core radiation fields.

## **2.2 Discussion of Chemistry Regimes**









## **2.3 Materials Integrity in the Reactor Coolant System**

### ***2.3.1 Corrosion Modes of Structural Materials***



### **2.3.2 Effects of Chemistry Parameters**

#### **2.3.2.1 PWSCC Mechanisms**



#### 2.3.2.2 Dissolved Oxygen

#### 2.3.2.3 Dissolved Hydrogen – Effects at Operating Temperatures















#### **2.3.2.4 Dissolved Hydrogen – Low Temperature Considerations**

#### 2.3.2.5 pH







#### 2.3.2.6 Lithium



#### **2.3.2.7 Analytical Evaluation of Effect of Lithium-pH History on PWSCC Susceptibility**

#### 2.3.2.8 Plant Experience Regarding Effects of Lithium and pH on PWSCC





**2.3.2.9 Chloride**

**2.3.2.10 Fluoride**

**2.3.2.11 Sulfate**



#### 2.3.2.12 Organics

#### 2.3.2.13 Zinc



## **2.4 Fuel Integrity Considerations**

### ***2.4.1 Chemistry Effects on Fuel Reliability***

#### 2.4.1.1 Cladding Corrosion





#### 2.4.1.2 Fuel Crud Deposition

## **2.4.2 Effects of Chemistry Parameters**

### **2.4.2.1 Dissolved Oxygen**



#### 2.4.2.2 Fluoride

#### 2.4.2.3 Aluminum, Calcium, Magnesium, and Silica





#### 2.4.2.4 Suspended Solids

#### 2.4.2.5 pH

#### 2.4.2.6 Lithium



#### 2.4.2.7 Zinc





### **2.4.3 PWR Axial Offset Anomaly**



## **2.5 Radiation Field Control**

### ***2.5.1 Sources of Radiation Fields***

### **2.5.2 Effects of Chemistry Parameters**

#### 2.5.2.1 Corrosion Product Release

#### 2.5.2.2 Particulate Transport

### 2.5.2.3 Soluble Transport



#### **2.5.2.4 Verification Tests and Plant Experience**



#### 2.5.2.5 Plant Data





#### 2.5.2.6 Zinc



### **2.5.3 Summary**



# 3

## POWER OPERATION CHEMISTRY CONTROL RECOMMENDATIONS

---

### 3.1 Introduction

In this section, chemistry control recommendations intended to serve as industry-consensus guidelines are presented. These recommendations are based on current technical understanding and industry experience. For less restrictive site-specific modifications to control parameters in these *Guidelines*, plant chemistry personnel must produce a written technical justification that addresses the relevant regulatory, fuel warranty, and safety implications of such modifications (see Section 4).

### 3.2 Reactor Coolant System (RCS) pH Optimization

#### 3.2.1 *Operating Recommendations*















---

*Power Operation Chemistry Control Recommendations*

### ***3.2.2 Transition to Constant pH Operation***



---

*Power Operation Chemistry Control Recommendations*

### **3.3 Control and Diagnostic Parameters**

### **3.4 Guideline Recommendations**

#### **3.4.1 Goals**

### **3.4.2 Corrective Actions**

## **3.5 Definitions of Terms Used in the Guidelines**

### **3.5.1 Plant Status**

### **3.5.2 Action Levels**

**3.5.2.1 Action Level 1**

**3.5.2.2 Action Level 2**

**3.5.2.3 Action Level 3**

**3.6 Guideline Values for Chemistry Parameters During Power Operation**

***3.6.1 Reactor Coolant System Guidelines***









### **3.6.2 Special Considerations**

#### **3.6.2.1 Axial Offset Anomaly**

#### **3.6.2.2 Zinc Addition**

#### **3.6.2.3 Extended Fuel Cycles**

#### **3.6.2.4 Operation With Unusual Levels of Lithium**

#### 3.6.2.5 Chemistry Program Modification

### **3.6.3 Primary System Makeup Water**

---

## **3.7 Control and Diagnostic Parameters, Frequencies, and Limits for Startup Chemistry**





# **4**

## **METHODOLOGY FOR PLANT-SPECIFIC OPTIMIZATION**

---

### **4.1 Introduction**

The purpose of this section is to provide a framework for plant chemistry personnel to develop an optimized primary chemistry program considering plant design, materials of construction, fuel design and cycle length, corrosion degradation history, regulatory commitments, fuel vendor warranty requirements, etc.

The recommended approach recognizes that nuclear power plants must consider a variety of issues in developing a primary water chemistry program and that these issues must be dealt with on a plant specific basis.

## **4.2 Primary Water Chemistry Variables and Options**

### ***4.2.1 Program Objectives***

### ***4.2.2 Parameters Impacting Structural Integrity***



#### 4.2.2.1 Chloride/Fluoride/Sulfate

#### 4.2.2.2 Dissolved Oxygen Control

#### 4.2.2.3 Hydrogen

#### 4.2.2.4 $\text{pH}_r$ (Lithium Control Parameter)

#### 4.2.2.5 Zinc

### ***4.2.3 Parameters With Negligible Impact on Structural Integrity***

#### 4.2.3.1 Silica

**4.2.3.2 Suspended Solids**

***4.2.4 Chemistry Control During Shutdowns and Startups***

**4.2.4.1 Shutdown Chemistry Program**

**4.2.4.2 Startup Chemistry Program**

**4.3 Optimization Methodology**

***4.3.1 Optimization Process***

#### **4.3.2 NEI SG Initiative Checklist**









# **5**

## **REFERENCES**

---

---

## *References*

---

## *References*

---

## *References*

---

## *References*

---

## *References*

---

## *References*

---

## *References*



---

## *References*

---

## *References*

---

## *References*

---

## *References*

---

## *References*

# A

## CALCULATION OF PHT AND DATA EVALUATION METHODOLOGIES

---

### 1.0 Calculation of $\text{pH}_T$

To provide a uniform basis for establishing a  $\text{pH}_T$  control program and for comparing observations at different plants, it is mandatory that industry personnel employ similar expressions for pertinent chemical equilibria, e.g., the ionization of boric acid. The recommended relations are given below.







---

*Calculation of pHT and Data Evaluation Methodologies*



---

*Calculation of pHT and Data Evaluation Methodologies*



---

*Calculation of pHT and Data Evaluation Methodologies*

## **2.0 Low Temperature pH, Boron, Lithium Calculations and Data**











### **3.0 Data Consistency (pH at 25°C/Conductivity at 25°C/Boron/Lithium)**







## **4.0**

## **5.0 Temperature and Pressure Dependence of pH**







## **6.0 Monitoring for Fuel Reliability**

## **7.0 Primary-to-Secondary Leak Monitoring**

## **8.0 References**

# ***B***

## **CHEMISTRY CONTROL OF SUPPORTING SYSTEMS**

---

### **1.0 Introduction**

Chemistry control practices in systems that interface with the reactor coolant system are discussed below. Specifically, selected system designs, the rationales for chemistry control, possible impacts on reactor coolant chemistry and industry experiences where impacts on RCS chemistry have been observed are discussed. Suggestions are provided on chemistry and radioactivity parameters to be monitored and the frequency of monitoring.

### **2.0 Letdown Purification System**

#### ***2.1 System Description***

## ***2.2 Selection Criteria for Purification Filters and Ion Exchange Resins***

## ***2.3 Performance Monitoring***



---

*Chemistry Control of Supporting Systems*



## **2.4 Selected Industry Experiences**

### **2.4.1 Resin Intrusions**

### **2.4.2 Chloride Elution**

### **2.4.3 Leachable Impurities**

### **2.4.4 Boron/Power Excursions**

**2.4.5 Lithium Excursions/Power Effects**

**2.4.6 Shutdown Sulfate Increases**

**2.4.7 Makeup Water Contamination**

### **3.0 Volume Control Tank**

#### ***3.1 System Description***

#### ***3.2 Chemistry Control and Technical Basis***



### ***3.3 Selected Industry Experiences***

#### **3.3.1 VCT Vapor Space Composition**

## **4.0 Pressurizer**

### ***4.1 System Description***

## **4.2 Chemistry Control and Technical Basis**

### **4.3 Industry Experience**

#### **4.3.1 Corrosion Observations**

#### **4.3.2 RCS Hydrogen Control**

#### **4.3.3 Chloride Contamination**

### **5.0 Boric Acid Storage**

#### ***5.1 System Description***

## ***5.2 Chemistry Control and Technical Basis***



### ***5.3 Industry Experience***

#### **5.3.1 Silica Transport**

#### **5.3.2 Boric Acid Crystallization**

### **5.3.3 Chloride Contamination**

### **5.3.4 Magnesium Contamination**

### **5.3.5 Sulfate Contamination**

## **6.0 Refueling Water Storage Tank**

### ***6.1 System Description***

### ***6.2 Chemistry Control and Technical Basis***



### **6.3 Industry Experience**

#### **6.3.1 Reactor Water Clarity**

#### **6.3.2 Resin Contamination**

#### **6.3.3 Silica Control**

#### **6.3.4 Chloride / Fluoride Contamination Due to Freon Intrusion**

### **7.0 Spent Fuel Pool Cooling and Cleanup System**

#### **7.1 System Description**

Normal makeup for the spent fuel pool comes from the RWSTs, with alternate makeup paths from the Boron Recycle System holdup tanks via the transfer canal, or from the demineralized water system. An emergency source of makeup can come from the condensate storage tanks or the service water system.

## ***7.2 Chemistry Controls and Technical Basis***



### **7.3 Industry Experience**

#### **7.3.1 Failure of Bundle Top Nozzles**

#### **7.3.2 Silica Control**

### **8.0 References**

# **C**

## **STATUS OF ENRICHED BORIC ACID (EBA) APPLICATION**

---

### **1.0 Introduction**

Boric acid is used in primary coolant of a PWR as a soluble reactivity control agent. Dissolved boric acid is referred to as a soluble poison or chemical shim because the  $^{10}\text{B}$  isotope has a high cross section for absorbing thermal neutrons. However, natural boron contains only 20 atom percent of the  $^{10}\text{B}$  isotope. The remaining 80% is  $^{11}\text{B}$ , which has a much smaller cross section for thermal neutron absorption. Enriching natural boric acid with  $^{10}\text{B}$  can reduce the concentration of boric acid in the coolant while retaining the required reactivity control.

### **2.0 Summary of EPRI Studies**



### **3.0 Plant Demonstrations of EBA**

## **4.0 References**

# **D**

## **AOA AND ULTRASONIC FUEL CLEANING**

---

### **1.0 Background**

The evolving economics of electric generation requires PWRs to operate with higher fuel duty and longer cycles. Sub-cooled nucleate boiling in the upper fuel spans is a consequence for such aggressively driven cores. Thermodynamic and hydraulic factors favor deposition of corrosion products on the boiling surfaces of the fuel, resulting in axially non-uniform deposition on high-duty fuel. Axially variable distribution of boron compounds in these fuel deposits is an important cause of axial offset anomaly (AOA).

### **2.0 Ultrasonic Fuel Cleaning Technology**

### **3.0 System Description**

## **4.0 Fuel Cleaning Efficacy**

## **5.0 Full-Reload Cleaning Results**

## **6.0 Fuel Cleaning Performance**



## **7.0 Conclusions**

## **8.0 References**



# **E**

## **OXYGEN AND HYDROGEN BEHAVIOR IN PWR PRIMARY CIRCUITS**

---

### **1.0 Summary**

Oxygen and hydrogen behavior in a PWR primary circuit are linked by the radiolysis reactions occurring in the core to the extent that they cannot normally co-exist in the coolant, other than upstream of the core. In normal operation and during shutdown the important aspects are – (1) what is the minimum hydrogen level to suppress radiolysis in the water phase in the core, (2) will sub-cooled nucleate boiling on fuel assemblies in the core deplete the hydrogen in the water phase below this minimum hydrogen concentration and (3) what is the effect of oxygen ingress into the RCS.

The concentrations of oxygen, hydrogen, hydrogen peroxide and other species in a PWR primary circuit are controlled by approximately 50 radiolytic and thermal reactions, all of which occur simultaneously as the coolant circulates around the circuit. The rate constants of these reactions are known over the full operating temperature range of the primary circuit and the behavior can be modeled with reasonable confidence. This appendix describes the overall behavior and is based on (1) and (2), which model oxygen/hydrogen concentrations in a typical Westinghouse 4-loop PWR.

### **2.0 Radiation Chemistry**

### **3.0 Minimum Hydrogen Concentrations at Full Power**





#### **4.0 The Effect of Voidage on Minimum Hydrogen Levels**

---

*Oxygen and Hydrogen Behavior in PWR Primary Circuits*

## **4.1 Metal Ion Chemistry**

## **5.0 Oxygen Ingress**

---

*Oxygen and Hydrogen Behavior in PWR Primary Circuits*





---

*Oxygen and Hydrogen Behavior in PWR Primary Circuits*



## **6.0 Startup Deoxygenation**

## **7.0 Spent Fuel Pool**

## **8.0 Conclusions**

## **9.0 References**



# ***F***

## **SAMPLING CONSIDERATIONS FOR MONITORING RCS CORROSION PRODUCTS**

---

### **1.0 Background on RCS Sampling Technology**



---

*Sampling Considerations for Monitoring RCS Corrosion Products*

## **2.0 Existing Sampling Practices**

### **3.0 Continuous Corrosion Product Sampling**

#### **3.1 Background**



---

*Sampling Considerations for Monitoring RCS Corrosion Products*









### ***3.2 Continuous Sampling and Analysis Methods***



---

*Sampling Considerations for Monitoring RCS Corrosion Products*



---

*Sampling Considerations for Monitoring RCS Corrosion Products*

### **3.3 Conclusions**

#### **4.0 Augmented Reactor Coolant Corrosion Product Sampling at Diablo Canyon and Catawba (26)**

---

*Sampling Considerations for Monitoring RCS Corrosion Products*



---

*Sampling Considerations for Monitoring RCS Corrosion Products*

---

*Sampling Considerations for Monitoring RCS Corrosion Products*

## **5.0 References**



---

*Sampling Considerations for Monitoring RCS Corrosion Products*

# **G**

## **REACTOR COOLANT RADIONUCLIDES**

---

This appendix provides suggestions with regard to possible methods for use in monitoring radionuclides in the reactor coolant system.

### **1.0 Formation of Radionuclides in the RCS**

---

*Reactor Coolant Radionuclides*





---

*Reactor Coolant Radionuclides*



---

*Reactor Coolant Radionuclides*



---

*Reactor Coolant Radionuclides*

**1.1 Radionuclides Formed by Fission**



---

*Reactor Coolant Radionuclides*





---

*Reactor Coolant Radionuclides*

***Fission Product Speciation***

## ***1.2 Radionuclides Formed by Activation***



---

*Reactor Coolant Radionuclides*



---

*Reactor Coolant Radionuclides*





## **2.0 Measurement of Radionuclides in the Reactor Coolant System**

### ***2.1 Examples of Measurement of Radionuclides by Adjusting Sample/Counting Parameters***



## **2.2 Identifying Unknown Gamma Ray Peaks**



---

*Reactor Coolant Radionuclides*



---

*Reactor Coolant Radionuclides*





### **3.0 Expected Concentrations and Trends of RCS Radionuclides**

#### **3.1 Fission Products**







### **3.2 Activation Product Trends**





## **4.0 References**



# **H**

## **DEFINITION OF HIGH DUTY CORE: A MEANS FOR EVALUATING THE PROPENSITY TO DEPOSIT CRUD ON FUEL ASSEMBLIES**

---

### **1.0 Background**

Plants with high fluid temperatures and high surface heat flux at the fuel clad have a portion of the total heat transfer to the coolant occur by sub-cooled nucleate boiling (SNB). Although favorable for thermal efficiency, the combination of high temperature and SNB leads to more severe duty on the fuel, and surface boiling is known to enhance the formation of corrosion product deposits (crud) on the cladding surface.

### **2.0 Definition**

---

*Definition of High Duty Core: A Means for Evaluating the Propensity to Deposit Crud on Fuel Assemblies*

### **3.0 Methodology**

### **4.0 Case Example**

## **5.0 High Duty – Medium Duty – Low Duty**

---

*Definition of High Duty Core: A Means for Evaluating the Propensity to Deposit Crud on Fuel Assemblies*

## **6.0 References**

---

*Definition of High Duty Core: A Means for Evaluating the Propensity to Deposit Crud on Fuel Assemblies*

## 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.

EPRI. Electrify the World

© 2003 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.



*Printed on recycled paper in the United States of America*

# **Pressurized Water Reactor Primary Water Chemistry Guidelines**

Volume 2, Revision 5

**1002884**

Final Report, September 2003

**NON-PROPRIETARY VERSION**

EPRI Project Managers  
P. Frattini  
K. Fruzzetti

# **Pressurized Water Reactor Primary Water Chemistry Guidelines**

Volume 2, Revision 5

**1002884**

Final Report, September 2003

**NON-PROPRIETARY VERSION**

EPRI Project Managers  
P. Frattini  
K. Fruzzetti



## **DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES**

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

**PWR Primary Water Chemistry Guidelines Committee**

## **ORDERING INFORMATION**

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520. Toll-free number: 800.313.3774, press 2, or internally x5379; voice: 925.609.9169; fax: 925.609.1310.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2003 Electric Power Research Institute, Inc. All rights reserved.

# CITATIONS

---

This report was prepared by

PWR Primary Water Chemistry Guidelines Committee

<b>AECL</b> J. Sawicki	<b>Exelon</b> R. Claes	<b>Pacific Gas &amp; Electric</b> C. Bowler
<b>Ameren UE</b> G. Gary, E. Olson, J. Small	<b>First Energy</b> V. Linnenbom, S. Slosnerick	<b>Progress Energy</b> N. Bach, P. Cross, E. Meyer, R. Thompson
<b>American Electric Power</b> K. Haglund	<b>Florida Power &amp; Light</b> C. Connelly, R. Litman, L. Michaud, G. Miller	<b>PSE&amp;G Nuclear LLC</b> J. Riddle
<b>AmerGen Energy</b> B. Walton	<b>Framatome ANP</b> W. Allmon, L. Lamanna	<b>Ringhals</b> P.-O. Andersson, B. Bengtsson
<b>Arizona Public Service</b> J. Santi	<b>GEBCO Engineering, Inc.</b> G. Brobst	<b>Rochester Gas and Electric</b> G. Jones
<b>Babcock &amp; Wilcox</b> P. King	<b>INPO</b> R. Schirmer	<b>South Carolina Electric &amp; Gas</b> F. Bacon
<b>British Energy</b> J. C. Bates, K. Garbett, Consultant	<b>iSagacity</b> J. Bates	<b>Southern California Edison</b> J. Muniga
<b>Constellation Energy</b> E. Eshelman	<b>Laborelec</b> E. Girasa, C. Laire	<b>Southern Nuclear</b> F. Hundley, D. Rickertsen
<b>Dominion Engineering</b> J. Gorman	<b>NMC</b> C. Jones, S. Lappegaard, J. McElrath	<b>STPNOC</b> D. Bryant, R. Ragsdale
<b>Dominion Resources</b> E. Frese	<b>NPP Krsko</b> K. Fink	<b>TXU Energy</b> K. Cooper, B. Fellers, L. Wilson
<b>Duke Energy</b> K. Johnson	<b>NWT Corp.</b> S. Sawochka	<b>TVA</b> D. Adams, D. Bodine
<b>Electricité de France</b> J.-L. Belzic	<b>Ontario Power Generation</b> K. Bagli	<b>Westinghouse</b> A. Byers, J. Kormuth, S. Lurie, N. Vitale
<b>Entergy</b> G. Dolese, D. Wilson	<b>OPPD</b> T. Dukarski	<b>WCNOC</b> J. Kuras, J. Truelove
<b>ELECTRIC POWER RESEARCH INSTITUTE</b> P. Frattini, Chairman; J. Blok, B. Cheng, J. Deshon, K. Fruzzetti, J. Hickling, H. Ocken, R. Pathania, C. Wood		

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 Primary Water Chemistry Guidelines: Volume 2, Revision 5*, EPRI, Palo Alto, CA: 2003. 1002884.

# REPORT SUMMARY

---

State-of-the art water chemistry programs help ensure the continued integrity of reactor coolant system (RCS) materials of construction and fuel cladding, ensure satisfactory core performance, and support the industry trend toward reduced radiation fields. These revised *PWR Primary Water Chemistry Guidelines*, prepared by a committee of industry experts, reflect the recent field and laboratory data on primary coolant system corrosion and performance issues. Volume 1 covers operating chemistry and Volume 2 covers startup and shutdown chemistry.

## Background

EPRI periodically updates the PWR water chemistry guidelines as new information becomes available and as required by NEI 97-06, Steam Generator Program Guidelines. The last revision of these Guidelines identified an optimum primary water chemistry program based on then-current understanding of research and field information. This revision provides further details with regard to primary water stress corrosion cracking (PWSCC), fuel integrity, and shutdown dose rates.

## Objective

To update the *PWR Primary Water Chemistry Guidelines, Revision 4*, published in 1999.

## Approach

A committee of industry experts, including utility specialists, nuclear steam supply system and fuel vendor representatives, Institute of Nuclear Power Operations representatives, consultants, and EPRI staff, collaborated in reviewing the available data on primary water chemistry, reactor water coolant system materials issues, fuel integrity and performance issues, and radiation dose rate issues. From these data, the committee generated water chemistry guidelines that all PWR nuclear plants should adopt. 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 operation.

## Results

Revision 5 of the *PWR Primary Water Chemistry Guidelines*, which provides recommendations for PWR primary systems of all manufacture and design, includes the following updates:

The Guidelines continue to emphasize plant-specific optimization of water chemistry to address individual plant circumstances. The committee revised guidance with regard to optimization to reflect industry experience gained since the publication of Revision 4. This revision continues to distinguish between prescriptive requirements and non-prescriptive guidance.

---

The revised Sections 2 and 3 of Volume 1 address the latest information on PWSCC of RCS materials, fuel cladding integrity and core performance, and radiation field control. The guidelines emphasize optimization of pH control programs with regard to maintaining system integrity, minimizing the potential for axial offset anomaly and excessive fuel deposits, use of zinc additions to minimize shutdown dose rates and mitigate PWSCC concerns, and ensuring that pH programs do not have adverse impacts on PWSCC or fuel cladding integrity.

The committee reviewed and revised shutdown and startup chemistry coverage in Volume 2 to reflect industry experience gained in this area since issuance of Revision 4. In particular, the technical basis for corrosion product transport and activity transport control were updated with the significant results of studies of fuel deposits from cores with significant local assembly steaming or core-wide high duty commensurate with axial offset anomaly.

The committee also updated or added several appendices to Volumes 1 and 2. These include new sections on RCS sampling, ultrasonic fuel cleaning technology, radiochemistry, definition of a high duty core index, and mid-cycle shutdown/startup decision logic.

### **EPRI Perspective**

This fifth revision of the *PWR Primary Water Chemistry Guidelines*, endorsed by the utility executives of the EPRI Steam Generator Management Project, represents another step in the continuing use of proactive chemistry programs to limit or control degradation of steam generator tubes and other structural parts. This revision documents the increased consideration of state-of-the art water chemistry programs to help ensure the continued integrity of reactor coolant system (RCS) materials of construction and fuel cladding, ensure satisfactory core performance, and support the industry trend toward reduced radiation fields. These revised *PWR Primary Water Chemistry Guidelines* reflect the recent field and laboratory data on primary coolant system corrosion and performance issues, which PWR operators can use to update their primary water chemistry programs.

### **Keywords**

PWRs

Water chemistry

Primary water stress corrosion cracking

Guidelines

Reactor coolant system

## ABSTRACT

---

Ensuring continued integrity of RCS materials of construction and fuel cladding and maintaining the industry trend toward reduced radiation fields requires continued optimization of reactor coolant chemistry. Optimization of coolant chemistry to meet site-specific demands becomes increasingly important in light of the movement toward extended fuel cycles, higher duty cores, increasingly stringent dose rate control, decreased refueling outage duration, and reduced operating costs. This document is the sixth in a series of industry guidelines on PWR primary water chemistry. Like each of the others in the series, it provides a template for development of a plant-specific water chemistry program.

Volume 2 of the PWR Primary Water Chemistry Guidelines covers startup and shutdown chemistry. In an era of ever shortening refueling outages, a primary goal of shutdown chemistry becomes minimizing the time from breaker trip to reactor vessel head lift while maintaining appropriate cautions to ensure safety. Shutdown chemistry evolutions can often become critical path depending on their relative success at reaching corrosion product transport and activity transport goals. Plant degassing procedures, forced oxidation results, and pressurizer oxygen control are but three important issues impacting on those goals. In an analogous way, the startup chemistry plan should strive to achieve power ascension in a minimum of time while still ensuring safety as well as meeting corrosion product transport goals that might impact core performance in the new cycle.

## EPRI FOREWORD

---

Chemistry optimization of pressurized water reactor (PWR) primary systems in recent times has been complicated by the demands of longer fuel cycles (i.e., higher initial boron concentrations), increased fuel duty (more subcooled boiling) and material/fuel corrosion concerns. Current utility concerns focus on minimizing costs without sacrificing materials integrity or safety. These Guidelines provide a template for a responsive chemistry program for PWR primary systems and the technical bases/supporting information for the program. It is the fifth revision of the Guidelines and considers the most recent operating experience and laboratory data. The Guidelines will be of interest to plant chemists, plant managers, chemical engineers, and engineering managers within utilities owning PWRs.

This is the second consecutive issue in which a second volume of the PWR Primary Water Chemistry Guidelines focuses on startup and shutdown chemistry. As noted for the previous revision, the decision to cover startup and shutdown chemistry in a separate volume was made for two main reasons: (1) the increasingly large amount of information regarding shutdown and startup chemistry contained in the Guidelines warrants a separate volume, and (2) locating the startup and shutdown information in a separate volume separates it from the NEI Steam Generator Initiative requirements of Volume 1. This Volume 2 contains no specific requirements (with limited exceptions identified in Tables 4-2 and 4-3) which must be met by utilities to be in compliance with the NEI 97-06 Initiative.

The combined shutdown and startup chemistry coverage in this Volume 2 was updated from that in Revision 4 of the Guidelines to reflect new information and experience gained since issuance of that revision. Volume 2 continues to provide: (1) technical discussions regarding plant experiences with different types of shutdown and startup chemistries; and (2) tables of demonstrated options, together with their perceived benefits and possible negative impacts, for refueling and mid-cycle outages. Section 2 is modified to include the substantially new information since Revision 4 on the nature of fuel deposits and their role in activity transport for plants operating high duty cores. Sections 3 and 4 contain industry guidance for shutdown and startup, respectively, together with accompanying discussion and technical support.

Volume 2 was prepared by a committee of experienced industry personnel through an effort sponsored by EPRI. Participation was obtained from chemistry, materials, steam generator, and fuels experts. Each EPRI-member utility operating a PWR participated in generation or review of these guidelines. Therefore, this document serves as an industry consensus for PWR primary water startup and shutdown chemistry control. This document is intended to be a set of guidelines which describes an effective, state-of-the-art program from which a utility can develop an optimized water chemistry plan for their plant. The philosophy embodied in this document has generic applicability, but can be adapted to the particular conditions of the utility

---

and the site. The detailed guidelines presented in Sections 3 and 4 and Volume 2 comprise a program that should serve as a model for the development of site-specific chemistry programs

Special acknowledgment is given to the following organizations for submitting first-hand experience through committee participation:

- Ameren UE
- American Electric Power
- AmerGen Energy
- Arizona Public Service
- Atomic Energy of Canada, Ltd.
- Babcock & Wilcox
- British Energy
- Constellation Energy
- Dominion Resources
- Duke Energy
- Electricité de France
- Entergy
- Exelon
- First Energy
- Florida Power & Light
- Framatome ANP
- INPO
- Laborelec (Belgium)
- NPP Krsko
- Nuclear Management Corporation (NMC)
- Omaha Public Power District
- Ontario Power Generation
- Pacific Gas & Electric Company
- Progress Energy
- Public Service Electric & Gas
- Ringhals (Sweden)
- Rochester Gas and Electric
- South Carolina Electric & Gas
- Southern California Edison
- Southern Nuclear Operating Co.
- South Texas Project Nuclear Operating Company
- Tennessee Valley Authority

- 
- TXU Energy
  - Westinghouse Electric
  - Wolf Creek Nuclear Operating Corp.

This committee was significantly assisted in its work by J. Gorman of Dominion Engineering; G. Brobst of GEBCO Engineering; J. Bates of iSagacity; K. Garbett, Consultant; H. Sims of AEA Technology; D. Kozin of NSSS Consulting Service; S. Sawochka of NWT Corporation; R. Litman, Consultant. In addition, the Committee would like to acknowledge the support and input of fuel specialists from EPRI-member utilities and vendors.

Relative to Revision 4 (March 1999) of these Guidelines, the major changes made to Volume 2 are as follows:

1. Descriptions of the morphology and properties of the newly discovered fuel crud constituents bonaccordite and zirconium oxide were added to Section 2, as well as a discussion of how their largely insoluble nature affects shutdown chemistry strategies.
2. Discussions were added and expanded of methods for monitoring and controlling hydrogen and oxygen concentrations in the pressurizer during shutdowns and startups.
3. Discussion was expanded regarding the use of acid reducing conditions during mid-cycle outages in a manner that might reduce AOA in high duty cores.
4. Plant experience was described that shows strong benefits from using the maximum practical RCS cleanup flow during shutdowns. This experience indicates that modifying system designs to increase the maximum cleanup flow rate can be beneficial.
5. Discussion was expanded of the need and methods to maintain oxidizing conditions in the reactor water through flood-up in order to minimize activity release during that operation.
6. Oxygen control strategies (including hydrogen degassing on shutdown and oxygen removal on startup) appropriate to plants that maintain a two-phase pressurizer are offered that are consistent with material integrity goals for pressurizer materials.
7. A variety of experiences were described regarding use or non-use of reactor coolant pumps during shutdown, including when adding hydrogen peroxide.
8. A discussion was added regarding the benefits of using higher cross linked resins.
9. Many changes were made to the startup and shutdown tables in Sections 3 and 4. These tables present the various options that are available, and their possible benefits and negative impacts. The changes reflect the experience gained since the last revision, including the topics noted above, and also reflect concerns that the industry must develop methods appropriate to PWR materials, temperature and stress intensities to assess the possibility of low temperature crack propagation (LTCP) in nickel-base alloys.



- 
10. A new Appendix was added that details an example of the decision logic that chemists may find useful when deciding what options are consistent with cycle chemistry goals when faced with unplanned mid-cycle outages whose duration may not be known precisely at the point in time of shutting down the reactor.

Paul L. Frattini, Chairman  
PWR Primary Water Chemistry Guidelines Revision Committee  
EPRI Nuclear Power Group  
March 2003

## ACRONYMS

---

AOA	Axial offset anomaly
BAST	Boric acid storage tank
BOC	Beginning of cycle
BRS	Boron recovery system.
BTRS	Boron thermal regeneration system
BWR	Boiling water reactor
CVCS	Chemical and volume control system. The term makeup system (MU) is used at some plants for the same system.
DEI	Dose equivalent iodine-131
DF	Decontamination factor
DHC	Debye-Huckel limiting slope
DRP	Discrete radioactive particle
$\bar{E}$	E-bar, Average disintegration energy
EBA	Enriched boric acid
ECP	Electrochemical potential
EPRI	Electric Power Research Institute
EOC	End of cycle
HDCI	High duty core index
HUT	Holdup tank.
IGSCC	Intergranular stress corrosion cracking
INPO	Institute of Nuclear Power Operations
LTCP	Low temperature crack propagation
LTOP	Low temperature overpressure
NEI	Nuclear Energy Institute
NSSS	Nuclear steam system supplier
NTU	Nephelometric turbidity units
PRT	Pressurized relief tank
PWR	Pressurized water reactor
PWSCC	Primary water stress corrosion cracking
RCP	Reactor coolant pump
RCS	Reactor coolant system. For purposes of these <i>Guidelines</i> , the RCS includes the pressurizer.
RFO	Refueling outage
RHR	Residual heat removal system. The terms decay heat (DH) system and shutdown cooling (SDC) system are used at some plants for the same system.
RWST	Refueling water storage tank. The term borated water storage tank (BWST) is used at some plants for the same tank.

---

SCC	Stress corrosion cracking
SFP	Spent fuel pool system. The term spent fuel cooling (SFC) system is used at some plants for the same system.
STP	Standard temperature and pressure
TOC	Total organic carbon
TSS	Total suspended solids
VCT	Volume control tank. The term makeup tank (MUT) is used at some plants for the same tank.

# CONTENTS

---

<b>1 INTRODUCTION .....</b>	<b>1-1</b>
<b>2 TECHNICAL BASIS FOR RCS CHEMISTRY CONTROL DURING HEATUP AND COOLDOWN .....</b>	<b>2-1</b>
2.1 Corrosion Product Behavior in the RCS .....	2-1
2.1.1 General Considerations .....	2-1
2.1.2 Fuel Cladding Deposits .....	2-1
2.1.3 Corrosion Films .....	2-3
2.1.4 Effects of Shutdown Chemistry Changes on Corrosion Products .....	2-4
2.1.4.1 Reductive Decomposition of Nickel Ferrites and Nickel Oxide .....	2-6
2.1.4.2 Oxidation Reactions and Deposit Dissolution During Shutdown/Cooldown .....	2-8
2.1.4.3 Considerations in Shutdown Chemistry Based on the Chemical Nature of the Fuel Deposit .....	2-13
2.1.4.4 Considerations due to Kinetics Limitations in Shutdown Evolutions .....	2-14
2.1.5 Axial Offset Anomaly .....	2-15
2.1.6 Impact of Oxygen on Corrosion Product Transport .....	2-17
2.2 Chemistry Changes During Shutdown/Cooldown .....	2-20
2.3 Methods for Evaluating Shutdown and Startup Chemistry .....	2-25
2.4 Plant Experience During Shutdowns .....	2-26
2.4.1 Expected Behavior .....	2-26
2.4.2 Selected Plant Experience .....	2-26
2.4.3 Shutdown Experience and Evaluations since Revision 4 .....	2-28
2.4.3.1 Corrosion Product Forms and Effects on Shutdown Chemistry .....	2-28
2.4.3.2 Conclusions from 1998-2001 Shutdown Chemistry Studies .....	2-29
2.4.4 Unexpected Release of Activated Particulates from Core Deposits .....	2-34
2.5 Iodine Behavior During Shutdowns .....	2-35
2.6 Effects of Zinc on Shutdown Chemistry (                      Experience) .....	2-37
2.6.1 Background .....	2-37

2.6.2 Operational Aspects .....	2-37
2.6.3 Shutdown Chemistry Considerations .....	2-37
2.6.4 Releases During Refueling Outages .....	2-39
2.7 Stress Corrosion Cracking of Stainless Steels in Pressurizers and Connections .....	2-40
2.8 Mid-cycle Outages.....	2-40
<b>3 PRINCIPLES OF CHEMISTRY CONTROL DURING SHUTDOWN .....</b>	<b>3-1</b>
3.1 Shutdown Chemistry Controls.....	3-1
3.1.1 General Principles .....	3-1
3.1.2 Shutdown Options Based on Recent Experience Requiring Plant-Specific Technical Justification .....	3-4
3.1.3 Evaluation of Shutdown Chemistry Data .....	3-8
3.2 Hydrogen Removal Practices.....	3-9
3.2.1 Introduction.....	3-9
3.2.2 Mechanical Degassing .....	3-10
3.2.3 Chemical Degassing.....	3-12
3.3 Activity Releases .....	3-13
3.4 RCS Oxygenation Practices.....	3-15
3.4.1 Introduction.....	3-15
3.4.2 Hydrogen Peroxide Treatment .....	3-16
3.4.2.1 Introduction .....	3-16
3.4.2.2 Hydrogen Peroxide Qualification .....	3-16
3.4.2.3 Coolant Oxygenation Results .....	3-17
3.4.3 Control of Refueling Water Clarity by Hydrogen Peroxide Treatment .....	3-18
3.5 Fission Product Control During Shutdowns.....	3-19
3.6 Control and Diagnostic Parameters, Monitoring Frequencies, and Limits for RCS Chemistry from Operation to Cold Shutdown.....	3-19
3.7 Utility Experience.....	3-24
3.7.1 Pre-Refueling Shutdown RC Lithium / pH Reduction .....	3-24
<b>4 PRINCIPLES OF CHEMISTRY CONTROL DURING STARTUP .....</b>	<b>4-1</b>
4.1 Post Refueling Startup and Mid-Cycle Chemistry Management Issues.....	4-1
4.2 Corrosion Product Behavior During Heatup .....	4-7
4.3 Reactor Coolant Oxygen Control Practices.....	4-8
4.3.1 Overview of RCS Oxygen Control Practices .....	4-8
4.3.2 Coolant System Oxygen Removal Practices.....	4-9

---

4.3.2.1 Mechanical Methods .....	4-9
.....	4-9
.....	4-9
.....	4-9
4.3.2.2 Residual Dissolved Oxygen Removal by Chemical Methods - Dissolved Oxygen Scavenging with Hydrazine .....	4-10
.....	4-11
4.3.3 Pressurizer Oxygen Control .....	4-11
4.4 VCT Operation and Hydrogen Control .....	4-12
4.5 Lithium Additions and pH Control.....	4-13
4.6 RCS Fill and Oxygen Control Sequence .....	4-13
4.7 Dilutions for Silica Control .....	4-14
4.8 Mid-Cycle Startups and Shutdowns .....	4-14
4.8.1 Mid-Cycle Shutdown Chemistry Considerations .....	4-14
4.8.2 Mid-Cycle Startup Chemistry Considerations .....	4-16
4.9 Control and Diagnostic Parameters, Frequencies, and Limits for Startup Chemistry .....	4-16
4.10 Example Utility Experience with Startup Chemistry .....	4-20
RCS / Pressurizer Startup Oxygen Control Process.....	4-20
<b>5 REFERENCES .....</b>	<b>5-1</b>
<b>A EXAMPLE RCS MID-CYCLE SHUTDOWN CHEMISTRY DECISION LOGIC .....</b>	<b>A-1</b>
References.....	A-6

## LIST OF FIGURES

---

Figure 2-1 Frequency distribution of the Ni/Fe ratio of PWR fuel deposits .....	2-3
Figure 2-2 Physical Representation of RCS Corrosion and Corrosion Product Deposit Layers .....	2-3
Figure 2-3 Approximate Stability Limits for Nickel Ferrites .....	2-7
Figure 2-4 Solubilization of Nickel Cobalt Ferrite in a Simulated Shutdown Test .....	2-10
Figure 2-5 Iron and Nickel Behavior for a Shutdown with Good Acid Reducing Chemistry (Oxygen Controlled in Makeup Water, Boric Acid, and RHR Loop) .....	2-11
Figure 2-6 Iron and Nickel Behavior for a Shutdown with Major Particulate Release (Oxygen not Controlled in Makeup Water, Boric Acid, and RHR Loop) .....	2-12
Figure 2-7 pH of RCS During Typical Refueling Shutdown .....	2-22
Figure 2-8 pH of RCS During Cooldown .....	2-23
Figure 2-9 pH of RCS During Mid-Cycle Cold Shutdown .....	2-23
Figure 2-10                      Normalized Total Nickel Released During Refueling Outages .....	2-31
Figure 2-11                      Normalized Total Normalized <sup>58</sup> Co Released During Refueling Outages .....	2-31
Figure 2-12                      Average Steam Generator Bowl Dose Rate .....	2-39
Figure A-1 CEOG Mid-Cycle Shutdown Chemistry Decision Logic .....	A-2

## LIST OF TABLES

---

Table 2-1 PWR Crud Incidents Attributable to Oxidizing Conditions .....	2-19
Table 3-1 Selected Chemistry and Operational Control Options for Refueling Outages and Cold Shutdowns .....	3-5
Table 3-2 Chemistry Surveillance During Preparation Phase.....	3-20
Table 3-3 Chemistry Surveillance During Baseline Phase .....	3-21
Table 3-4 Chemistry Surveillance During Shutdown Phase .....	3-22
Table 3-5 Recommended Chemistry Surveillance During Shutdown (Reactor Subcritical to Flood Up) RCS Hot Leg or Letdown Sample .....	3-23
Table 4-1 Chemistry and Operational Control Options for Startups Following Shutdowns with RCS Open .....	4-4
Table 4-2 Reactor Coolant System Cold Shutdown Control Parameters (Reactor <250°F (121°C)).....	4-17
Table 4-3 Reactor Coolant System Startup Control Parameters (Reactor Subcritical and >250°F (121°C)) .....	4-18
Table 4-4 Reactor Coolant System Startup Chemistry Diagnostic Parameters (Following Fill-and-Vent to Reactor Critical) .....	4-19



# 1

## INTRODUCTION

---

This volume of the *PWR Primary Water Chemistry Guidelines* describes the technical basis and specific recommendations for chemistry control of reactor coolant during shutdown and startup. Industry experience continues to indicate that appropriate control of reactor coolant chemistry during plant shutdowns and startups can help control or reduce localized high radiation areas, personnel exposures, and refueling water turbidity problems.

# 2

## TECHNICAL BASIS FOR RCS CHEMISTRY CONTROL DURING HEATUP AND COOLDOWN

---

### 2.1 Corrosion Product Behavior in the RCS

#### *2.1.1 General Considerations*

Metallic materials exposed to water in the RCS owe their corrosion resistance to a protective layer of chemically stable metal oxide that is formed in the operating environment. Although corrosion rates are very low for Alloys 600, 690, and 800 and stainless steel, which make up the greatest part of system surface area, metal oxidation products are released from such surfaces and are transported throughout the system.

The process by which corrosion and activation products are transported within the RCS involves a complex set of interacting chemical and physical mechanisms that continues to be studied.

#### *2.1.2 Fuel Cladding Deposits*

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

### **2.1.3 Corrosion Films**

***2.1.4 Effects of Shutdown Chemistry Changes on Corrosion Products***

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

#### 2.1.4.1 Reductive Decomposition of Nickel Ferrites and Nickel Oxide

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*



#### 2.1.4.2 Oxidation Reactions and Deposit Dissolution During Shutdown/Cooldown





---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

#### 2.1.4.3 Considerations in Shutdown Chemistry Based on the Chemical Nature of the Fuel Deposit

#### 2.1.4.4 Considerations due to Kinetics Limitations in Shutdown Evolutions

### **2.1.5 Axial Offset Anomaly**



---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

#### ***2.1.6 Impact of Oxygen on Corrosion Product Transport***

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*



## **2.2 Chemistry Changes During Shutdown/Cooldown**



---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*





---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

## **2.3 Methods for Evaluating Shutdown and Startup Chemistry**

## **2.4 Plant Experience During Shutdowns**

### ***2.4.1 Expected Behavior***

### ***2.4.2 Selected Plant Experience***



### ***2.4.3 Shutdown Experience and Evaluations since Revision 4***

#### **2.4.3.1 Corrosion Product Forms and Effects on Shutdown Chemistry**

#### **2.4.3.2 Conclusions from 1998-2001 Shutdown Chemistry Studies**

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*





---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*



#### ***2.4.4 Unexpected Release of Activated Particulates from Core Deposits***

## **2.5 Iodine Behavior During Shutdowns**

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

## **2.6 Effects of Zinc on Shutdown Chemistry (Diablo Canyon Experience) (27, 30)**

### **2.6.1 Background**

### **2.6.2 Operational Aspects**

### **2.6.3 Shutdown Chemistry Considerations**

---

*Technical Basis for RCS Chemistry Control During Heatup And Cooldown*

#### ***2.6.4 Releases During Refueling Outages***



## **2.7 Stress Corrosion Cracking of Stainless Steels in Pressurizers and Connections**

## **2.8 Mid-cycle Outages**



# 3

## PRINCIPLES OF CHEMISTRY CONTROL DURING SHUTDOWN

---

### 3.1 Shutdown Chemistry Controls

#### 3.1.1 *General Principles*

Three global shutdown chemistry strategies have been used successfully prior to peroxide treatment:

- High temperature acid reducing conditions
- Low temperature acid reducing conditions
- No acid reducing conditions

---

*Principles of Chemistry Control During Shutdown*



***3.1.2 Shutdown Options Based on Recent Experience Requiring Plant-Specific Technical Justification***









### **3.1.3 Evaluation of Shutdown Chemistry Data**

## **3.2 Hydrogen Removal Practices**

### **3.2.1 Introduction**

### **3.2.2 Mechanical Degassing**



the tank contents through a hydrogen recombiner. Fission gases remain in the tank to decay to acceptable levels for release.

### **3.2.3 Chemical Degassing**

### **3.3 Activity Releases**





## **3.4 RCS Oxygenation Practices**

### **3.4.1 Introduction**

### **3.4.2 Hydrogen Peroxide Treatment**

#### **3.4.2.1 Introduction**

#### **3.4.2.2 Hydrogen Peroxide Qualification**

#### 3.4.2.3 Coolant Oxygenation Results

### ***3.4.3 Control of Refueling Water Clarity by Hydrogen Peroxide Treatment***

### **3.5 Fission Product Control During Shutdowns**

### **3.6 Control and Diagnostic Parameters, Monitoring Frequencies, and Limits for RCS Chemistry from Operation to Cold Shutdown**





---

*Principles of Chemistry Control During Shutdown*





### **3.7 Utility Experience**

#### ***3.7.1 D.C. Cook Pre-Refueling Shutdown RC Lithium / pH Reduction***



# 4

## PRINCIPLES OF CHEMISTRY CONTROL DURING STARTUP

---

### 4.1 Post Refueling Startup and Mid-Cycle Chemistry Management Issues

Strategic decisions such as the method of filling and venting the reactor coolant system, the methods of oxygen control, the impacts of placing RCPs in operation, the timing of lithium additions and hydrogen controls should be developed for each plant as part of the chemistry optimization program.











---

*Principles of Chemistry Control During Startup*

## **4.2 Corrosion Product Behavior During Heatup**

## **4.3 Reactor Coolant Oxygen Control Practices**

### ***4.3.1 Overview of RCS Oxygen Control Practices***

### **4.3.2 Coolant System Oxygen Removal Practices**

#### **4.3.2.1 Mechanical Methods**

#### 4.3.2.2 Residual Dissolved Oxygen Removal by Chemical Methods - Dissolved Oxygen Scavenging with Hydrazine

*Dissolved Oxygen Removal by Hydrogen Addition*

**4.3.3 Pressurizer Oxygen Control**

#### **4.4 VCT Operation and Hydrogen Control**

## **4.5 Lithium Additions and pH Control**

## **4.6 RCS Fill and Oxygen Control Sequence**



## **4.7 Dilutions for Silica Control**

## **4.8 Mid-Cycle Startups and Shutdowns**

### ***4.8.1 Mid-Cycle Shutdown Chemistry Considerations***



#### **4.8.2 Mid-Cycle Startup Chemistry Considerations**

### **4.9 Control and Diagnostic Parameters, Frequencies, and Limits for Startup Chemistry**



---

*Principles of Chemistry Control During Startup*



## **4.10 Example Utility Experience with Startup Chemistry**





# **5**

## **REFERENCES**

---

---

## *References*

---

## *References*

# **A**

## **EXAMPLE RCS MID-CYCLE SHUTDOWN CHEMISTRY DECISION LOGIC**

---

The chemistry options for shutdown in midcycle outages are discussed in Sections 2 and 3 of this volume.

---

*Example RCS Mid-Cycle Shutdown Chemistry Decision Logic*

---

*Example RCS Mid-Cycle Shutdown Chemistry Decision Logic*

---

*Example RCS Mid-Cycle Shutdown Chemistry Decision Logic*





## **References**

## 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.

EPRI. Electrify the World

© 2003 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.



*Printed on recycled paper in the United States of America*

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA  
800.313.3774 • 650.855.2121 • [uskepri@epri.com](mailto:uskepri@epri.com) • [www.epri.com](http://www.epri.com)