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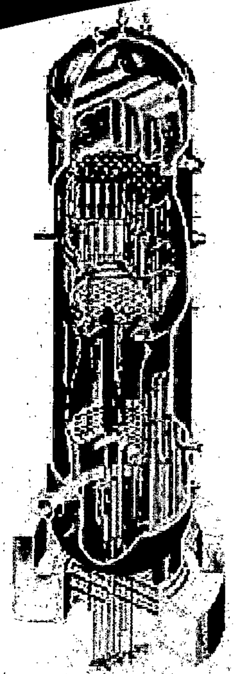
2019 TECHNICAL REPORT

BWRVIP-62NP-A (2018 Update): BWR Vessel and Internals Project

Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection



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BWRVIP-62NP-A (2018 Update): BWR Vessel and Internals Project

Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection

3002014434NP

Final Report, May 2019

EPRI Project Manager
R. Pathania

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES [✓ NO]

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FINAL NRC SUPPLEMENTAL SAFETY EVALUATION OF BWRVIP-62-A: JULY 6, 2018

In accordance with NRC topical report requirements, the Final NRC Supplemental Safety Evaluation of BWRVIP-62-A immediately follows this page. Other NRC and BWRVIP correspondence on this subject are included in appendices B through F.

Note: The front matter of this report was revised as shown in the Record of Revisions. No changes were made in the rest of the report.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 6, 2018

Mr. Tim Hanley, Chairman
ATTN: Debbie Rouse
BWR Vessel and Internals Project
1300 West W.T. Harris Boulevard (Building 1)
Charlotte, NC 28262

SUBJECT: FINAL SUPPLEMENTAL SAFETY EVALUATION RELATED TO BWRVIP-62-A, "BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION," USE OF ONLINE NOBLE METAL CHEMISTRY IN BOILING WATER REACTORS

Dear Mr. Hanley:

By letter dated January 24, 2018 (Agencywide Documents Access and Management System Accession (ADAMS) No. ML18033A323), the Boiling Water Reactor Vessel and Internals Project (BWRVIP) stated that the BWRVIP had issued the following interim guidance to its members:

> U.S. plants utilizing all forms of HWC [hydrogen water chemistry] and crediting HWC shall meet the conditions and limitations of BWRVIP-62-A. In the case of plants utilizing OLNC [online noble metal chemistry], this means they shall meet the Category 3a NMCA [noble metal chemical addition] parameters and implementation steps (including platinum loading) of Tables 3-5 and 3-8. This guidance is issued as NEI 03-08 'Needed' guidance.

The January 24, 2018, letter supplemented information in BWRVIP-62, "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection."

By letter dated May 15, 2018, the NRC staff issued its draft safety evaluation (SE) (ADAMS Accession No. ML18107A607).

By letter dated May 31, 2018 (ADAMS Accession No. ML18155A347), the BWRVIP informed the NRC staff that there was no proprietary information, inaccuracies, or needed clarifications in the draft SE.

The NRC staff has found the use of OLNC acceptable subject to the limitations specified in the NRC SE. The final SE defines the basis for our acceptance.

In accordance with the guidance provided on the NRC website, we request that BWRVIP publish approved proprietary and non-proprietary versions of BWRVIP-62 within six months of receipt of this letter. The approved versions shall incorporate this letter and the enclosed final SE after the title page.

If future changes to the NRC's regulatory requirements affect the findings in the NRC staff SE, the BWRVIP will be expected to revise the BWRVIP-62 appropriately. Licensees referencing this BWRVIP-62 would be expected to justify its continued applicability or evaluate their plant using the revised BWRVIP-62.

If you have any questions or require any additional information, please feel free to contact the NRC Project Manager for the review, Joseph Holonich at (301) 415-7297 or Joseph.Holonich@nrc.gov.

Sincerely,

Dennis C. Morey, Chief
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Docket No.: 99902016

Enclosure:
Final Safety Evaluation

Cc: Mr. Bob Carter
BWR Vessel and Internals Project
1300 West W.T. Harris Boulevard (Building 1)
Charlotte, NC 28262

SUPPLEMENTAL FINAL SAFETY EVALUATION

BY THE OFFICE OF NUCLEAR REACTOR REGULATION ON

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT REPORT TOPICAL REPORT-108705 (BWRVIP-62): "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION"

USE OF ONLINE NOBLE METAL CHEMISTRY IN BOILING WATER REACTORS

DOCKET NO. 99902016

1.0 INTRODUCTION

By letter dated April 21, 2010, the U.S. Nuclear Regulatory Commission (NRC) staff issued its final safety evaluation (SE) (Ref. 1) of Boiling Water Reactor Vessel and Internals Project (BWRVIP) Topical Report-108705, "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)." By letter dated May 13, 2011, the BWRVIP transmitted to the NRC "BWRVIP-62-A: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection," EPRI Technical Report 1021006, November 2010 (Ref. 2). BWRVIP-62-A incorporated changes from responses to NRC staff requests for additional information (RAIs), NRC staff recommendations from its final SE, and other necessary revisions since the original publication of BWRVIP-62. By letter dated February 16, 2012, the NRC staff communicated its final verification of BWRVIP-62-A (Ref. 3).

BWRVIP-62-A accepted for use the noble metal chemical addition (NMCA) process and hydrogen water chemistry (HWC), moderate (HWC-M), as bases for claiming relief from certain BWRVIP inspections. As described in BWRVIP-62-A, NMCA is a process in which noble metal is added in batches to the reactor coolant system during refueling outages, and small amounts of hydrogen are continuously injected during plant operation. The NRC staff SE for BWRVIP-62 accepted for use three criteria that plants applying noble metal chemistry must meet to demonstrate mitigation of Intergranular stress corrosion cracking (IGSCC):

1) Measured electrochemical potential (ECP) less than or equal to -230 millivolts (mV).
2) Measured hydrogen-to-oxygen molar ratio greater than or equal to 3.
3) Measured catalyst loading greater than or equal to a specific proprietary value.

BWRVIP-62-A is referenced by other BWRVIP inspection and evaluation guidelines, and implementation of water chemistry in accordance with BWRVIP-62-A is credited to reduce the inspections identified in those documents.

By letter dated January 24, 2018, (Ref. 4) the BWRVIP stated that the BWRVIP had issued the following interim guidance to its members:

Enclosure

> U.S. plants utilizing all forms of HWC and crediting HWC ... shall meet the conditions and limitations of BWRVIP-62-A. In the case of plants utilizing OLNC [online noble metal chemistry], this means they shall meet the Category 3a NMCA parameters and implementation steps (including platinum loading) of Tables 3-5 and 3-8. This guidance is issued as NEI 03-08 'Needed' guidance.

2.0 SUMMARY OF THE BWRVIP-62 REPORT

See Section 2.0 of Reference 1.

3.0 EVALUATION

The NRC staff has reviewed the BWRVIP interim guidance described in the BWRVIP's January 24, 2018, letter to NRC. The OLNC method includes introduction of noble metal periodically during plant operation (Ref. 5). In its review of the acceptability of the use of OLNC to provide noble metal protection, the NRC staff determines:

1) The acceptance criteria contained in BWRVIP-62-A are performance criteria which the plant must demonstrate that it meets to reduce the inspections.

2) These criteria reflect the condition of the metal/environment interface at the locations specified in BWRVIP-62-A, which controls the susceptibility of the subject component to IGSCC.

3) Based on the need to meet these performance criteria, any method to introduce noble metal levels sufficient to meet these criteria will provide reasonable assurance that effective mitigation of IGSCC has been achieved and inspections can be reduced in those areas specified in BWRVIP-62-A.

Because OLNC is one method to introduce noble metal, plant-specific implementation of OLNC which demonstrates conformance with the performance criteria of BWRVIP-62-A can utilize the inspection credit as specified in sources referencing BWRVIP-62-A, consistent with the BWRVIP interim guidance provided in its January 24, 2018, letter to the NRC.

4.0 CONCLUSIONS

The NRC staff concludes that plants which apply OLNC and meet the criteria of a Category 3a plant in BWRVIP-62-A may claim inspection credit afforded by sources that reference BWRVIP-62-A.

5.0 REFERENCES

1. Safety Evaluation for Boiling Water Reactor Vessel and Internals Project (BWRVIP) Topical Report BWRVIP-62, "Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection," EPRI TR-108705, April 21, 2010 (ADAMS Accession No. ML100850009).

2. Project 704, Re-Transmittal of "BWRVIP-62-A: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection," May 13, 2011 (ADAMS Accession No. ML111370728).

3. NRC Approval Letter for "BWRVIP-62-A: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection" (TAC No. ME6327), February 16, 2012 (ADAMS Accession No. ML120310164).
4. Electric Power Research Institute - Status of BWRVIP-62 Revision and Inspection Relief for BWR Piping Welds and Internal Components with Hydrogen Injection, January 24, 2018 (ADAMS Accession No. ML18033A323).
5. EPRI Progress Report dated January 2010, "Chemical Mitigation Protects BWR Internals and Could Justify Less-Frequent Inspection Intervals," http://mydocs.epri.com/docs/CorporateDocuments/Newsletters/NUC/2010-01/01c.html

Principal Contributor: Jeffrey Poehler

Date: July 6, 2018

FINAL NRC SAFETY EVALUATION OF BWRVIP-62: APRIL 21, 2010

In accordance with NRC topical report requirements, the final NRC Safety Evaluation of BWRVIP-62 immediately follows this page. Other NRC and BWRVIP correspondence on this subject are included in appendices B through F.

Note: The changes proposed by the NRC in this Safety Evaluation as well those proposed by the BWRVIP in response to NRC Requests for Additional Information have been incorporated into the current version of the report (BWRVIP-62-A).

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

April 21, 2010

Mr. Rick Libra
Exelon
Chairman, BWR Vessel and Internals Project
Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94304-1395

SUBJECT: FINAL SAFETY EVALUATION FOR BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT TOPICAL REPORT-108705 (BWRVIP-62), "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION (BWRVIP-62)" (TAC NO. ME0043)

Dear Mr. Libra:

By letter dated December 31, 1998, as supplemented by letters dated August 1, 2001 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML012140408), May 19, 2003 (ADAMS Accession No. ML031430145), and December 17, 2004 (ADAMS Accession No. ML043560323), the Electric Power Research Institute submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval Boiling Water Reactor Vessel and Internals Project (BWRVIP) report TR-108705 (BWRVIP-62), "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection." A non-proprietary version of BWRVIP-62 was sent on March 7, 2000, and is available in ADAMS under Accession No. ML003691846. BWRVIP-62 contains a discussion of the technical basis for relief from current inspection requirements for Boiling Water Reactor (BWR) reactor vessel internal components (RVIs) that are protected from intergranular stress corrosion cracking by the injection of hydrogen into the reactor coolant.

On January 30, 2001, the NRC staff issued its initial Safety Evaluation (SE) (ADAMS Accession No. ML010370141) for BWRVIP-62. This SE contained open items which are described in more detail in Section 3.0 of this SE. In response to the open items contained in the NRC staff's SE dated January 30, 2001, the BWRVIP provided technical information related to the implementation of the BWR Vessel Internals Application model in a letter dated August 1, 2001, followed by supplemental information in letters dated May 19, 2003, and December 17, 2004. The NRC staff has reviewed the responses, and its comments and recommendations regarding these responses are stated in Section 3.0 of this SE.

X

By letter dated July 22, 2008, the NRC staff issued an SE (ADAMS Accession No. ML081840740) for BWRVIP-62 to address the technical and supplemental information provided to resolve the open items. The BWRVIP reviewed this SE and identified a few technical inaccuracies and addressed its position on some of the mitigation aspects which were transmitted to the NRC staff in letter dated October 30, 2008 (ADAMS Accession No. ML083080078). The NRC staff reviewed the BWRVIP's submittal, made appropriate technical corrections, and incorporated them into a draft SE dated November 9, 2009 (ADAMS Accession No. ML092720245). Attachment 1 of the draft SE contains a detailed explanation of the NRC staff's review with respect to the BWRVIP's positions and the technical inaccuracies that were found in the NRC staff's SE dated July 22, 2008.

By letter dated January 25, 2010 (ADAMS Accession No. ML100280039), the BWRVIP commented on the draft SE of November 9, 2009. The NRC staff's disposition of these comments is contained in Attachment 1 of this SE.

The final SE includes an expectation that the approved version of BWRVIP-62 will be revised to include the information the BWRVIP provided in its letters dated August 1, 2001, May 19, 2003, and December 17, 2004. This issue is discussed in Section 3.3 of the SE.

The NRC staff has reviewed BWRVIP-62 and finds that this BWRVIP report is acceptable for referencing in licensing documentation to the extent specified and under the limitations delineated in the BWRVIP report and in the enclosed SE. The SE defines the basis for our acceptance of BWRVIP-62.

Our acceptance applies only to material provided in the subject BWRVIP report. We do not intend to repeat our review of the acceptable material described in the BWRVIP report. When the BWRVIP report appears as a reference in licensing documentation, our review will ensure that the material presented applies to the specific plant involved. Licensees will be expected to implement the provisions of BWRVIP-62, subject to the limitations in the enclosed SE, as part of their BWRVIP program unless deviations from the requirements are justified. Licensees shall identify such deviations to the NRC staff in accordance with BWRVIP program requirements.

In accordance with the guidance provided on the NRC website, we request that BWRVIP publish accepted proprietary and non-proprietary versions of this Topical Report (TR) within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include an "-A" (designating accepted) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, BWRVIP and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

Thomas B. Blount

Thomas B. Blount, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No.: 704

Enclosure:
Final SEs (Non-proprietary and Proprietary versions)

cc w/encl: See next page

cc:

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION (SE) BY THE OFFICE OF NUCLEAR REACTOR REGULATION BOILING WATER REACTOR (BWR) VESSEL AND INTERNALS PROJECT (BWRVIP) REPORT TOPICAL REPORT (TR)-108705 (BWRVIP-62): "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION"

BWRVIP

PROJECT NO. 704

1.0 INTRODUCTION

1.1 Background

By letter dated December 31, 1998, as supplemented by letters dated August 1, 2001 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML012140408), May 19, 2003 (ADAMS Accession No. ML031430145), and December 17, 2004 (ADAMS Accession No. ML043560323), the Electric Power Research Institute (EPRI) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval BWRVIP report TR-108705 (BWRVIP-62), "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection." A non-proprietary version of BWRVIP-62 was sent on March 7, 2000, and is available in ADAMS under Accession No. ML003691846. BWRVIP-62 contains a discussion of the technical basis for relief from current inspection requirements for BWR reactor vessel internal components (RVIs) that are protected from intergranular stress corrosion cracking (IGSCC) by the injection of hydrogen into the reactor coolant.

On January 30, 2001, the NRC staff issued its initial SE (ADAMS Accession No. ML010370141) for BWRVIP-62. This SE contained open items which are described in more detail in Section 3.0 of this SE. In response to the open items contained in the NRC staff's SE dated January 30, 2001, the BWRVIP provided technical information related to the implementation of the BWR Vessel Internals Application (BWRVIA) model in a letter dated August 1, 2001, followed by supplemental information in letters dated May 19, 2003, and December 17, 2004. The NRC staff has reviewed the responses, and its comments and recommendations regarding these responses are stated in Section 3.0 of this SE.

ENCLOSURE 1

By letter dated July 22, 2008, the NRC staff issued an SE (ADAMS Accession No. ML081840740) for BWRVIP-62 to address the technical and supplemental information provided to resolve the open items. The BWRVIP reviewed this SE and identified a few technical inaccuracies and addressed its position on some of the mitigation aspects which were transmitted to the NRC staff in letter dated October 30, 2008 (ADAMS Accession No. ML083080078). The NRC staff reviewed the BWRVIP's submittal, made appropriate technical corrections, and incorporated them into a draft SE dated November 9, 2009 (ADAMS Accession No. ML092720245). Attachment 1 of the draft SE contains a detailed explanation of the NRC staff's review with respect to the BWRVIP's positions and the technical inaccuracies that were found in the NRC staff's SE dated July 22, 2008.

By letter dated January 25, 2010 (ADAMS Accession No. ML100280039), the BWRVIP commented on the draft SE of November 9, 2009. The NRC staff's disposition of these comments is contained in Attachment 1 of this SE.

1.2 Purpose

The NRC staff reviewed BWRVIP-62 to determine whether this report provides an adequate technical basis for implementing modified inspection requirements for BWR RVIs that are protected from IGSCC based on the methods described in BWRVIP-62. This SE considered the role of neutron fluence on IGSCC, the rates of crack propagation, aspects of the physical chemistry, effects of electrochemical corrosion potential (ECP), coolant flow and noble metal chemical application (NMCA) on IGSCC susceptibility, the radiolysis and ECP models, and an assessment of the effectiveness of hydrogen injection.

1.3 Organization of the SE

Section 2.0 of this SE summarizes BWRVIP-62. Section 3.0 evaluates each topic in Section 2.0 of this SE. Section 3.0 also evaluates how the BWRVIP addressed the open items from the NRC staff's SE dated January 30, 2001. Section 4.0 summarizes the conclusions resulting from this SE.

2.0 SUMMARY OF BWRVIP-62

BWRVIP-62 contains a discussion of the technical basis for implementing modified inspection requirements for BWR RVIs that are protected from IGSCC based on the methods described in BWRVIP-62 (involving the injection of hydrogen into the reactor coolant).

Section 1.0 of BWRVIP-62 describes the two primary techniques for protecting RVIs from IGSCC by means of hydrogen injection, or hydrogen water chemistry (HWC). The first of these techniques is moderate hydrogen water chemistry (HWC-M) whereby hydrogen is injected into the reactor coolant at rates higher than would typically be used to protect piping. The second of these techniques is NMCA whereby a continuous injection of a small amount of hydrogen is supplemented by an occasional batch injection of a small amount of noble metal compounds which act as catalysts for the recombination reactions. This section also presents a comprehensive survey of previous cracking events in BWR RVIs due to IGSCC and studies which indicate the effectiveness of HWC in mitigating IGSCC.

Section 2.0 of BWRVIP-62 describes radiolysis/ECP computer models used to determine the effectiveness of hydrogen injection techniques for mitigating IGSCC. The use of high purity water in BWRs for the neutron moderator and primary coolant, coupled with water radiolysis due to neutron and gamma radiation, results in high ECP and increases the susceptibility of RVIs to IGSCC. The effectiveness of mitigation techniques can be assessed by directly measuring ECP (as measured by a standard hydrogen electrode) at a specific location of interest in the RVIs. However, direct ECP measurements at specific locations in the RVIs can be cumbersome due to the relative inaccessibility of some RVIs. Therefore, the technical basis described in BWRVIP-62 included supplementary techniques that do not depend on direct measurement of the ECP at specific locations in the RVIs.

The BWRVIP developed a computer model known as BWRVIA (BWR Vessel and Internals Application for Radiolysis and ECP Analysis) as a supplementary technique to calculate the radiolysis chemistry and ECP values of the reactor coolant system (RCS) at a specific component location in the RVIs. In addition, the calculated chemistry and ECP values obtained from the BWRVIA model can be correlated with the measurements of other plant parameters (i.e., oxygen concentration, main steam line radiation levels, etc.). Figure 2-8 of BWRVIP-62 shows the comparison between model calculation and plant measured data including 162 data points from 20 sensors at mid-core, core plate, recirculation flange, and drain line locations in 6 plants. The measurements agree reasonably well with calculated results considering the uncertainties in all involved variables. The BWRVIP proposes to use this BWRVIA model as a tool to monitor plant water chemistry and ECP data. The NRC staff did not review the BWRVIA model. The NRC staff did, however, evaluate the results of the application of the model, which were submitted in BWRVIP-62 and in the responses to requests for additional information in letters dated August 1, 2001, May 19, 2003, and December 17, 2004.

In Section 3.0 of BWRVIP-62, the current operating history is reviewed and correlated to the corresponding plant water chemistry. A conclusion is drawn that HWC-M is able to reduce crack initiation and crack growth. Methods are described using hydrogen injection and NMCA with hydrogen injection. All of the above are in combination with ECP measurements or calculations. The effect of HWC-M and NMCA on the Nitrogen-16 isotope radiation of the main steam line is discussed. The crack growth correlation developed in BWRVIP-14, "Evaluation of Crack Growth in BWR Stainless Steel Reactor Vessel Internals" (Reference 1), is used to develop expected factors of reduction in crack growth rate corresponding to the expected reduction in ECP.

Section 4.0 discusses current inservice inspection requirements and concludes implementation of either HWC-M or NMCA would result in lower IGSCC propagation rates which would justify inspection relief. With respect to the crack growth model and radiolysis results, an inspection program for the RVIs can be developed based on factors of improvement (FOI) for plants that have implemented either HWC-M or NMCA. The FOI calculated for each RVI, based on modeling results, would be applied to revise the inspection interval established in the various BWRVIP inspection and flaw evaluation (I&E) reports. The BWRVIP will propose and request

NRC staff approval of revised inspection intervals for the RVIs for plants that have implemented either HWC-M or NMCA.

3.0 EVALUATION

BWR austenitic stainless steel and nickel-based alloy RVIs have experienced IGSCC, leading to degradation and potential safety concerns. Therefore, the NRC staff found it necessary for BWR licensee's to perform regular inspections of RVIs to provide adequate assurance of their structural integrity. The BWRVIP developed several I&E guidelines for several safety-related RVIs which were reviewed and found acceptable by the NRC staff. However, due to the difficulty and expense of these RVI inspections, licensees find it desirable to demonstrate that fewer inspections are necessary when suitable IGSCC mitigation steps are taken.

Two primary techniques have been used to ensure mitigation of IGSCC in BWR RVIs using HWC. The first technique involves utilizing higher hydrogen injection rates than would typically be used to protect recirculation piping (1 to < 2 ppm). This technique is referred to as HWC-M and its goal is to provide sufficient additional hydrogen in order to lower ECP to protective levels in the lower plenum. The second protective technique is NMCA, which involves a continuous injection of a small amount of hydrogen (to give a minimum threshold value of hydrogen-to-oxygen molar ratio in the single phase liquid region) supplemented by an occasional batch injection of catalytic noble metal compounds. Since both processes can protect RVIs from environmentally-assisted cracking degradation, the effective implementation of either HWC-M or NMCA at a BWR is considered an adequate basis for the implementation of a modified inspection program for RVIs.

With respect to the crack growth model and radiolysis results, an inspection program for the RVIs can be developed based on FOIs for plants that have implemented either HWC-M or NMCA. The FOI calculated for each RVI, based on modeling results, would be applied to revise the inspection interval established in the various BWRVIP I&E guidelines. The BWRVIP will propose revised inspection intervals for the RVIs for plants that have implemented either HWC-M or NMCA.

In its initial SE for BWRVIP-62 issued by letter dated January 30, 2001, the NRC staff found that the guidance provided in BWRVIP-62 is acceptable, pending the resolution of certain open items. In this SE, the NRC staff evaluates the BWRVIP response to each of these open items.

3.1 Technical Basis for HWC-M and NMCA

Section 1.0 of BWRVIP-62 provides a description of HWC techniques for mitigating IGSCC and presents evidence for the effectiveness of these techniques. The effectiveness of the HWC-M and NMCA is monitored by measuring the ECP of the metal surface, the primary parameter in assessing the availability of hydrogen in the water surrounding RVIs and, for NMCA, noble metal compounds on the surface. A protection potential of -230 mV or below at operating temperature can be achieved by the addition of hydrogen to the feedwater or the addition of hydrogen with noble metal compounds deposited on the metal surface. For plants implementing NMCA, noble metals, such as platinum, palladium, or rhodium, can be used as a catalyst for the recombination of hydrogen with oxygen. Consequently, the hydrogen concentration required for plants implementing NMCA will be substantially lower than that required for plants implementing HWC-M.

BWRVIP-62 also provides technical requirements for maintaining the conductivity of the RCS water at a specific threshold level so that the susceptibility of the RVIs to IGSCC is minimized. The conductivity of RCS water is affected by the presence of ionic impurities which increases the susceptibility of RVIs to IGSCC. The NRC staff has reviewed and accepted the approach taken to control the conductivity of the RCS water below a threshold level.

In its initial SE dated January 30, 2001, the NRC staff issued five open items relevant to Section 1.0 of BWRVIP-62. The five open items (grouped into four areas) previously identified were: the effect of flow rate on the RCS water ECP, the role of neutron fluence and the effect of radiation on crack growth rates, the effect of radiation on ECP, and the assessment of HWC-M effectiveness with changing radiation levels. In addition, the NRC staff evaluated an issue not previously identified as an open issue: the effectiveness of HWC-M and NMCA in deep cracks. The NRC staff's evaluation of the BWRVIP responses to the five open items and the newly identified issue, are discussed below.

3.1.1 Effect of Flow Rate on ECP and Susceptibility of RVIs to IGSCC

This open item was identified as Open Item 3.2.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Under BWR normal water chemistry (NWC) conditions, the oxidation and reduction reactions on passive steel surfaces are limited by the mass transport of oxygen to the surface for the oxygen reduction reaction. Mass transport increases as flow increases and, thus, ECP is expected to increase with flow velocity.

By letter dated March 15, 2001, the BWRVIP submitted report TR-112314, "BWR Vessel and Internals Project, Effect of Flow Rate on Intergranular Stress Corrosion Cracking and Electrochemical Corrosion Potential" (BWRVIP-64) (ADAMS Accession No. ML010780076), for information only, in response to the NRC staff's request. BWRVIP-64 discusses crack tip chemistry and the effect of flow rate on crack growth kinetics. The NRC staff did not formally review BWRVIP-64. However, the NRC staff did review Section 1.4 of BWRVIP-62, which provides data on the effect of flow rate on ECP values and crack growth rates, Figures 1-4 and 1-5, which were developed based on the detailed information provided in BWRVIP-64. The NRC staff agrees that crack growth rates remain low at higher flow rates because at higher flow rates the impurities and aggressive ions are flushed out of the crack tip region. Subsequently, the chemical concentration gradient between the tip of the crack and the bulk solution is reduced, resulting in the reduction of crack growth rates. The NRC staff concludes that the explanation provided in BWRVIP-62 regarding the effect of flow rate on the ECP and crack growth rates is a reasonable explanation to support the laboratory results and therefore, the NRC staff considers this open item closed.

3.1.2 Effectiveness of HWC-M and NMCA in Deep Cracks

This issue was not identified in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. However, by letter dated December 17, 2004, the BWRVIP issued a supplementary response in which it discussed the effectiveness of HWC-M and NMCA in deep cracks (crack depths equal to or greater than [Content Deleted - EPRI Proprietary Information]). Theoretical and experimental studies have been conducted to determine crack mouth and crack tip pH and ECP and their role in IGSCC for stainless steels in HWC-M and NWC environments. The results of these studies are discussed in "Modeling of Water and Material Chemistry Effects on Crack Tip Chemistry and Resulting Crack Growth Kinetics" by Peter Andresen (Reference 2) which has been submitted to the NRC staff for information only. In cracks, the ECP gradient between the crack mouth and crack tip causes the pH at the crack tip to become more acidic and more concentrated in anionic species such as chlorides and sulfates which may be present in bulk water. The IGSCC process in NWC is driven by a combination of an aggressive crack tip environment, applied and residual stresses, and a susceptible material. In an HWC-M or NMCA environment, the ECP is low at both the crack tip and the crack mouth. Therefore, there is no ECP gradient and in the absence of a potential gradient, the pH at the crack tip stays near neutral and there is little concentration of anionic species. In an HWC-M or NMCA environment, the IGSCC process slows down because the crack tip environment is less aggressive. Studies have also shown that localized crack tip chemistry can exist in cracks when they reach depths of [ ] or more. However, in an HWC-M environment, crack growth tests show that deep cracks respond in the same way as shallower cracks.

Based on the information submitted for its review, the NRC staff concludes that plant operators can claim credit for an effective HWC-M environment when they: (1) maintain an established hydrogen concentration at the crack location for at least 80 percent of the time that the reactor water temperature is equal to or greater than 200^0 F and (2) maintain the ECP value of the metal surface at -230 mV or below at operating temperature. Since the hydrogen concentration at plants implementing NMCA is lower than that at plants implementing HWC-M, the NRC staff concludes that plants implementing NMCA should maintain an established molar ratio at the RVI location for at least [Content Deleted - EPRI Proprietary Information] of the time that the reactor water temperature is equal to or greater than 200^0 F (i.e., [Content Deleted - EPRI Proprietary Information] more time than that required at plants implementing HWC-M) in order to achieve the same protection against IGSCC in deep cracks. The NRC staff concludes that the ECP value of the NMCA treated metal surface shall be maintained at -230 mV or below to achieve protection from IGSCC.

The NRC staff understands that licensees follow the inspection guidelines that are provided in the relevant BWRVIP reports associated with each component and monitor the growth rates of deep cracks to verify that adequate protection is achieved with an effective HWC-M or NMCA environment. The NRC staff requests that the BWRVIP revise BWRVIP-62 to include the information provided in the BWRVIP letter dated December 17, 2004, which describes the effect of an HWC-M or NMCA environment on the crack growth rates of deep cracks. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated December 17, 2004.

3.1.3 Role of Neutron Fluence and the Effect of Radiation on Crack Growth Rates

This issue was identified as Open Items 3.1.1 and 3.1.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. This discussion focuses on crack growth rates due to irradiation assisted stress corrosion cracking in RVIs with an exposure to neutron fluences up to 5×10^{20} n/cm^2 (i.e., E > 1 MeV). When BWRVIP-62 was originally submitted, no data was available regarding crack growth rates in welds that are exposed to a neutron fluence value of 5×10^{20} n/cm^2 and above. Therefore, BWRVIP-62 evaluates taking credit for HWC and/or NMCA in welds that are exposed to neutron fluences less than 5×10^{20} n/cm^2. To provide a technical basis for evaluating the effectiveness of HWC and/or NMCA in welds with exposure to neutron fluences equal to or greater than 5×10^{20} n/cm^2, the BWRVIP, by letter dated December 20, 2001, submitted for NRC staff review and approval report 10030318, "Crack Growth Rates in Irradiated Stainless Steels in BWR Internal Components" (BWRVIP-99) (ADAMS Accession No. ML020020313). BWRVIP-99 provides technical requirements for determining crack growth rates for welds exposed to neutron fluences above 5×10^{20} n/cm^2, and fluences equal to or less than 3×10^{21} n/cm^2. The NRC staff approved BWRVIP-99 by letter dated July 29, 2005 (ADAMS Accession No. ML052150325). BWRVIP-99 can be used for evaluating crack growth rates in welds with exposure to neutron fluences above 5×10^{20} n/cm^2 and fluences equal to or less than 3×10^{21} n/cm^2 provided they comply with all the conditions specified in the NRC staff's SE for this report. The NRC staff requests that the BWRVIP revise the BWRVIP-62 report to state that the crack growth rates specified in BWRVIP-99 shall be used for evaluating welds that are exposed to neutron fluences above 5×10^{20} n/cm^2, and fluences equal to or less than 3×10^{21} n/cm^2. Based on this evaluation, the NRC staff considers this issue closed.

3.1.4 Effect of Radiation on ECP

This issue was identified as Open Item 3.2.1 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Previous research work has shown that IGSCC susceptibility and crack growth rates depend on the ECP of stainless steels in BWR environments. The ECP threshold limit for IGSCC is a function of the following: radiation exposure, concentrations of impurities in the coolant, and the microstructure and composition of the steel. BWRVIP-62 states that the ECP threshold limit for IGSCC initiation in irradiated Type 304 stainless steel may be as high as -140 mV. Since there is a limited amount of data to support this value, the NRC staff requested that the BWRVIP retain the more conservative ECP threshold limit of -230 mV for the irradiated stainless steel materials. In its response dated August 1, 2001, the BWRVIP concurred with the NRC staff and agreed to use an ECP threshold limit of -230 mV. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP response letter dated August 1, 2001.

3.1.5 Assessment of HWC-M Effectiveness with Change in Radiation Levels

This issue was identified as Open Item 3.2.6 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Previous work suggests that all radiolysis analyses have shown that radiation levels in the downcomer region have a strong effect on the rate of the hydrogen-oxygen recombination reaction. Since the radiation level in the downcomer varies throughout core life, the actual degree of mitigation due to HWC-M and/or NMCA will also vary. In its response by letter dated August 1, 2001, the BWRVIP stated that the radiolysis/ECP model (i.e., the BWRVIA model) will be used for both the beginning and end of life of a fuel cycle. The end of the fuel cycle should represent the most conservative case (i.e., there should be an increase in ECP at the end of the cycle). The NRC staff agrees with the proposal for using the BWRVIA model to calculate the total oxidant content at both the beginning and end of life of a fuel cycle, with the end of fuel cycle case being the most conservative. The BWRVIA model (discussed in Section 3.2 of this SE) takes into consideration the effect of radiation on the hydrogen-oxygen recombination reaction. These calculations should take into consideration the uncertainties that are associated with the application of the model. The NRC staff requests that BWRVIP-62 be revised to include the information provided in the BWRVIP response to Open Item 3.2.6 sent by letter dated August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001.

3.2 Radiolysis and ECP models

Section 2.0 of BWRVIP-62 describes radiolysis/ECP computer models used to determine the effectiveness of hydrogen injection techniques for mitigating IGSCC. Section 2.0 of BWRVIP-62 also describes the basic concepts used in the application of the mathematical BWRVIA model used to establish the effectiveness of HWC-M/NMCA. For HWC plants, the BWRVIA model will be used to determine chemistry conditions and the ECP at various locations in the RVIs measured as a function of feedwater hydrogen injection rate. The BWRVIA model will be benchmarked against the ECP measurement made at the plant of interest or at other plants, known as "sister plants," that are radiolytically identical and have similar operational characteristics. For NMCA plants, the BWRVIA will be benchmarked against measurement of the molar ratio in reactor coolant samples at the plant of interest or at sister plants. Previous results have indicated that plants of identical design and operation respond in a similar manner to the hydrogen injection rate. The BWRVIP defines sister plants as any pair or group of BWRs that are demonstrated to be radiolytically equivalent by a validated and benchmarked radiolysis model. Ordinarily, the effectiveness of the model can be ascertained by the measurement of the chemistry conditions and the ECP at the location of interest in the RVIs. However, the measurement of chemistry and ECP at remote locations in the RVIs is very cumbersome and not practical. Therefore, the BWRVIP proposes using the BWRVIA model to calculate the ECP value and total oxidant content of the RCS water at the location of interest.

Section 2.0 of BWRVIP-62 discusses the application of the BWRVIA model to correlate with the two secondary parameters (feedwater hydrogen flow rate or concentration and normalized main steam line radiation) used to ensure the availability of HWC-M at the subject location. For the NMCA plants, the secondary parameters will include hydrogen-to-oxygen molar ratio and feedwater hydrogen flow rate or concentration. BWRVIP-62 states that if a good correlation is established between the calculated ECP value and the secondary parameters, then the secondary parameters can be used to assess the availability of hydrogen and/or NMCA at the desired location. A minimum of two secondary parameters, preferably feedwater hydrogen injection rate (or concentration) and main steam line radiation for HWC-M plants needs to be monitored. Additional secondary parameters for NMCA plants will include the measured value of hydrogen-to-oxygen molar ratio. The secondary parameter data will be collected, maintained, and correlated to supplement the ECP probe data. The BWRVIP in its submittal dated December 17, 2004, identified additional secondary parameters in a revision to Table 3-5 of the BWRVIP-62 report.

The BWRVIA model calculations include several parameters (e.g., mass flow, reactor power, feedwater hydrogen, oxygen). The BWRVIP also submitted data related to the application of the BWRVIA model in establishing correlation between the following parameters:

(1) calculated and measured steam oxygen concentrations;

(2) calculated and measured recirculation system hydrogen concentrations; and

(3) calculated and measured recirculation system oxidant concentrations.

The NRC staff did not review the BWRVIA model; however, the NRC staff did evaluate the results of the application of the model, and finds that there is good agreement between the calculated and measured ECP values (at a few locations in some of the BWR RVIs). The NRC staff finds that Section 2.0 of BWRVIP-62 adequately provides the basic concepts used in the BWRVIA model which is used to calculate the chemistry conditions and the ECP values at remote locations in the RVIs (i.e., where ECP values can not be measured easily). The NRC staff, in its initial SE dated January 30, 2001, requested that the BWRVIP discuss the validity of the BWRVIA model and the subsequent BWRVIP responses to NRC staff issues are discussed below.

The radiolysis model was discussed in Open Item 3.2.4 which was identified in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. For the past 10 years, the radiolysis model has undergone many changes. These changes include a refinement of the description of the primary system and the dose rate modeling of the ex-core regions and an updating of the neutron/gamma dose rates (the G values). The NRC staff requested that the BWRVIP provide a discussion of the significant differences between G values used in BWRVIP-62 and the G values used in similar approaches in Taiwan and Japan for analyzing the impact of HWC (References 3 and 4). The NRC staff also requested that results from a broader range of plants be included in a revised BWRVIP-62 in order to validate the capability of the model to predict water chemistries. Although numerous correlations of in-plant measurements are given in Figures 3-1 to 3-11 of BWRVIP-62, comparative model results in the referenced Appendix A of the BWRVIP-13 report, "Modeling Hydrogen Water Chemistry for BWR Applications" (Reference 5) are not presented in terms of the proposed secondary parameters. Because of this difference in presentation, it is not possible to determine whether the model results are representative of the range of behavior observed in the reactor vessel.

In its supplementary response sent by letter dated August 1, 2001, the BWRVIP stated that the G values, reaction rate constants, and some of the radiolysis schemes in the BWRVIA model were based on state-of-the-art techniques/information from the late 1980s. At that time, the integrated set of constants gave the best correlation with plant measurements. It was recognized that model inputs would have a range of uncertainties that would in turn result in uncertainties in the predictions. The approach used to address these uncertainties was to compare the model predictions of hydrogen, oxygen, and ECP obtained from specific locations to in-plant measurements of these same parameters obtained from the same locations.

The calculated and measured hydrogen and oxygen data obtained from the recirculation system of four plants, and the comparison of measured to calculated steam hydrogen and steam oxygen data presented in BWRVIP-62, indicate a close agreement between the measured and predicted hydrogen values in the reactor water. ECP values calculated by the model were compared with plant ECP measurements obtained at mid-core, core plate, recirculation flange and bottom head drain line locations. The measured data included 162 data points from 20 ECP probes that were installed at the aforementioned locations. The current BWRVIA model shows good agreement with plant chemistry data, as well as with plant ECP data obtained at specific locations in a limited number of plants. However, the data that was obtained from the [Content Deleted - EPRI Proprietary Information] plants show inconsistencies between the calculated and measured ECP values at the lower head region. The BWRVIP did not provide any explanation for this inconsistency. The BWRVIP, however, acknowledges that the model inputs have a range of uncertainties that would in turn result in uncertainties in predictions. The BWRVIP is planning to refine the model and reduce uncertainties in the model predictions, particularly in the lower head region. The BWRVIP proposes to submit its review of the BWRVIA models discussed in References 3 and 4 of this SE, along with additional research data on the ECP model related to the lower head region. The NRC staff will review these items when they are submitted for review.

As stated above, for HWC-M plants there are inconsistencies between the calculated and measured ECP values for RVIs obtained from the lower head region. Therefore, the NRC staff concludes that the BWRVIA model requires validation which can be achieved by installing an ECP probe specifically in this region. That is, if credit is desired for HWC-M and/or NMCA protection for lower head region components, an ECP measurement must be made in the lower head region volume. The reference electrode may be mounted inside a local power range monitor (LPRM) that has been modified to receive cooling water flow from the lower vessel head region, or in flanges off the bottom head drain line or reactor water clean up supply line (with needed corrections that are to be taken into account for the decomposition of hydrogen peroxide in the drain line). For validated BWRVIA model predictions, HWC credit can be claimed for RVIs in the lower head region when the BWRVIA ECP value of the RVI is -230 mV or below and total oxidant content is [ ] or less. To ensure the validity of the BWRVIA model predictions, the NRC staff expects the BWRVIA model to predict a conservative ECP value. HWC credit can be claimed for RVIs in the lower head region provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number when the measured value is -230 mV. If the difference in ECP value is a positive number then the calculated ECP value per the BWRVIA model is less conservative. Hence, to use BWRVIA model predictions for HWC credit, adjustment factors must be developed based on a correlation between the measured and calculated (per the BWRVIA model) ECP values. When multiple valid ECP measurements are available, the most conservative (highest) ECP value should be used to establish the feedwater hydrogen concentration at which IGSCC is mitigated. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value.

For NMCA plants, IGSCC mitigation must be demonstrated and molar ratio predictions of the BWRVIA model must be validated by measuring ECP of an oxidized stainless steel surface that was treated with NMCA. The ECP measurement can be made at external locations using RCS sample flow and the measured ECP value shall be -230 mV or less and a minimum molar ratio measured at given location shall be 3.

The NRC staff requests that the BWRVIP update BWRVIP-62 to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.4 sent by letter August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP response dated August 1, 2001.

3.3 HWC Effectiveness Assessment

In Section 3.0 of BWRVIP-62, the BWRVIP discusses the methodology for assessing the effectiveness of the use of HWC-M and NMCA in RCS water which is essential in mitigating IGSCC in RVIs. The BWR plants are categorized based on the verification methodology used for assessing the availability of HWC-M and/or NMCA. The categorization of the BWR plants and their characteristics are shown in Table 3.1 of this SE.

Category 1 plants use hydrogen to reduce the oxygen in the RCS water, and the hydrogen availability is assessed by measuring the ECP of the RVIs at the location of interest. These plants will use this measured ECP value as a primary parameter for ensuring the effectiveness of HWC-M at that location. In addition, the BWRVIP proposes to implement continuous monitoring of two secondary parameters (e.g., feedwater hydrogen flow rate or concentration and normalized main steam line radiation) to ensure the availability of HWC-M at the subject location. Details regarding the verification methodology for assessing the availability of HWC-M in Category 1 plants are discussed in Section 3.3.3.1 of this SE.

Category 2 plants use hydrogen to reduce the oxygen in the RCS water, and the hydrogen availability is assessed by calculating the ECP of the RVIs at the location of interest by using the BWRVIA model. Details regarding the verification methodology for assessing the availability of HWC-M in Category 2 plants are discussed in Section 3.3.3.2 of this SE.

Plants implementing NMCA additions have two categories, Category 3a and Category 3b. Category 3a plants use ECP measurements and noble metal catalyst loading as primary parameters followed by continuous monitoring of two secondary parameters (e.g., measured value of hydrogen-to-oxygen molar ratio and the feedwater hydrogen flow rate or concentration) to ensure the availability of NMCA at the subject location. Category 3b plants use noble metal catalyst loading and the measured value of hydrogen-to-oxygen molar ratio as primary parameters followed by continuous monitoring of two secondary parameters (e.g., calculated value of hydrogen-to-oxygen molar ratio and feedwater hydrogen flow rate or concentration) to ensure the availability of NMCA at the subject location. No ECP measurements are taken in Category 3b plants. Details regarding the verification methodology used to assess the availability of NMCA in Category 3a and Category 3b plants are discussed in Section 3.3.3.3 and 3.3.3.4 of this SE respectively.

3.3.1 Physical Chemistry Aspects of the HWC and/or NMCA Program

This issue was identified as Open Item 3.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. In its response sent by letter dated August 1, 2001, the BWRVIP proposed to incorporate changes to BWRVIP-62 regarding the following topics: (1) correlation of ECP measurements with the secondary parameters, (2) conductivity transients, (3) definition of an effective HWC-M, and (4) definition of an effective NMCA program. The NRC staff's evaluation of these topics is discussed below.

3.3.1.1 ECP Measurements

The BWRVIP proposes to use two reference electrodes to measure ECP as a primary parameter for Category 1 plants. The BWRVIP letter of August 1, 2001, indicates that the ECP measurements for Category 1 plants will be correlated with secondary parameters, preferably feedwater hydrogen injection rate or concentration and normalized main steam line radiation levels. The NRC staff finds that the method of using the correlated secondary parameters to assess the effectiveness of HWC-M when the ECP probes fail is acceptable. The NRC staff concludes that maintaining a good correlation between ECP measurements and the secondary parameters is essential in monitoring effective HWC-M in RVIs. Additional methods using validated BWRVIA models or sister plant data are acceptable to verify the effectiveness of HWC-M if these methods are used in conjunction with secondary parameters. It is the NRC staff's conclusion that in the absence of ECP measurements (i.e., failure of the ECP probe), reliable and continuous monitoring of secondary parameters is essential to ensure that an effective level of protection is being maintained at the location of interest in the RVIs. The NRC staff understands that the reliability and accuracy of the secondary parameters can be maintained if these parameters are validated with in-situ measurements of the ECP. The BWRVIP intends to validate the secondary parameters using an ECP probe once every ten years and [Content Deleted - EPRI Proprietary Information]. The NRC staff accepts this approach because it has previously accepted this method in its evaluation of Open Item 3.8 contained in its SE sent by letter dated September 15, 2000 (Reference 6), for BWRVIP report TR-113932, "BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)" (Reference 7).

To ensure adequate margin, the BWRVIP proposes to use a higher measured hydrogen-to-oxygen molar ratio for the NMCA plants (3 or more instead of 2 or more). BWRVIP-62, as supplemented by the BWRVIP responses, provides data that support the aforementioned position. The NRC staff reviewed the BWRVIP data and concludes that adequate mitigation of IGSCC in the RVIs is achieved when the hydrogen-to-oxygen molar ratio of 3 or more is maintained when measured in RCS water for NMCA plants. This value is consistent with the value recommended by General Electric. NMCA plants will implement a monitoring program that measures two secondary parameters to evaluate the adequacy of NMCA additions. The data submitted indicates that a good correlation is achieved between the measured ECP values and the secondary parameters.

Therefore, the NRC staff concludes that Category 3a plants (i.e., plants that implement NMCA and use ECP measurements as a primary parameter) maintaining a hydrogen-to-oxygen molar ratio of 3 or more (measured in RCS water) will adequately mitigate IGSCC in RVIs. The ECP probes will be exposed to reactor water and may be located within the vessel, in the bottom head drain, in the reactor water cleanup system or in a recirculation line or in external monitoring stations such as the Mitigation Monitoring Skid that is exposed RCS water from these locations. The BWRVIP states that if a plant is unable to maintain a hydrogen-to-oxygen molar ratio of 3 or more due to high radiation dose levels, a plant-specific analysis can be performed to demonstrate adequate mitigation at a lower molar ratio (between 2 and 3). However, NRC staff approval is required when intending to take plant-specific credit for an effective NMCA program when a hydrogen-to-oxygen molar ratio is programmatically maintained below 3.

3.3.1.2 Conductivity Transients

The BWRVIP response to this issue, sent by letter dated August 1, 2001, indicates that when the reactor water conductivity exceeds the action level limit of 0.3 µS/cm specified in BWRVIP report TR-103515-R2 "BWR Water Chemistry Guidelines – 2000 edition" (BWRVIP-79) (ADAMS Accession No. ML003722483), sent by letter dated June 2, 2000, for more than 24 hours, only the time in excess of 24 hours should be subtracted from the acceptable HWC-M available time. The NRC staff accepts this response because it has previously accepted this method in its SE (Open Item 3.8) for the BWRVIP-75 report (References 6 and 7). The BWRVIP recommends that contributions due to soluble iron may be subtracted from the measured conductivity for plants starting up with NMCA. The NRC staff accepts this response because the soluble iron in RCS water does not participate in the corrosion process, and the soluble iron does not affect the crack growth rate in RVIs.

3.3.1.3 Effective HWC-M Program

BWRVIP-62, as supplemented by the BWRVIP responses, provides data which indicate that a reduction in crack growth rates in RVIs can be achieved by controlling and monitoring HWC-M availability and by maintaining the ECP at a value equal to or less than -230 mV. The BWR Owner's Group conducted in-plant measurements of ECP in 21 BWRs that are operating with HWC-M. This discussion summarizes the results associated with the effectiveness of HWC-M in recirculation system piping. The BWRVIP presented data which demonstrated that the ECP value obtained for a given feedwater hydrogen injection rate varied with component location. The BWRVIP stated that mitigation of IGSCC can be achieved when hydrogen is available for at least 80 percent of the time that the reactor water temperature is equal to or greater than 200^0 F, at an ECP value of -230 mV or below. Based on the review of the data, the NRC staff agrees with this conclusion. The BWRVIP response states that when hydrogen injection is interrupted, no credit should be given for this time when calculating HWC-M availability. The interrupted time, in its entirety, should be counted as time that HWC-M is unavailable. The NRC staff concurs with this approach because it ensures that the calculation of the crack growth rate is based on a conservative calculation of the availability of HWC-M.

3.3.1.4 Effective NMCA Program

The BWRVIP in its response sent by letter dated August 1, 2001, states that effective NMCA is obtained for the plants when hydrogen is available to establish a molar ratio of hydrogen to oxygen greater or equal to 2 in RCS water and that, for periods of equal availability, NMCA is equivalent to HWC if both achieve an ECP of less than or equal to -230mV. As discussed in Section 3.1.2 of this SE, the NRC has concluded that plants implementing NMCA must maintain these conditions at least [Content Deleted - EPRI Proprietary Information] of the time that the reactor water temperature equal to or greater than 200^0 F. Direct measurement of the ECP can be used to demonstrate that the ECP is -230mV or below at operating temperature for stainless steel treated with noble metals exposed to RCS water. In addition, the BWRVIP reiterated that a reduction in crack growth rate in the RVIs can be achieved by controlling and monitoring the molar ratio of hydrogen to oxygen and NMCA addition, which will maintain the ECP at a value equal to or less than -230mV at operating temperature. BWRVIP-62, as supplemented by BWRVIP responses, provides adequate data to substantiate this claim. The NRC staff reviewed the submitted data and concludes that adequate mitigation of IGSCC in the RVIs of an NMCA plant is achieved when the measured secondary parameters correlate to the measured ECP of -230 mV or below.

The NRC staff requests that the BWRVIP revise BWRVIP-62 to address the information stated in the BWRVIP response to Open Item 3.2 sent by letter dated August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001.

3.3.2 Noble Metal Chemical Application/Additions

This issue was identified as Open Item 3.2.3 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. In its response sent by letter dated August 1, 2001, and supplemented by letter dated May 19, 2003, the BWRVIP addressed the issue related to hydrogen-to-oxygen molar ratio (Open Item 3.2.3) in NMCA plants. Details of this Open Item and the NRC staff's evaluation are discussed in Section 3.3.1.1 of this SE. As noted in Section 3.3.1.1, the NRC staff found the BWRVIP response acceptable.

3.3.3 ECP Model

This issue was identified as Open Item 3.2.5 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. The BWRVIA model in BWRVIP-62 is an empirical correlation relating concentrations of H_2, O_2, H_2O_2, and flow velocity to ECP. The results from six plants indicate that individual plant data appears to cluster either above or below the trend line, indicating that ECP cannot be simply estimated on the basis of the standard deviation based on the whole population of data. However, when grouped by plant, the data do not appear to be randomly distributed about the mean trend line. The NRC staff requested that the BWRVIP address the accuracy of the ECP measurements and the discrepancies between multiple ECP measurements. The ECP models applicable to the three categories of plants are addressed in Sections 3.3.3.1 (Category 1), 3.3.3.2 (Category 2), 3.3.3.3 (Category 3a), and 3.3.3.4 (Category 3b) of this SE.

In its response sent by letter dated August 1, 2001, supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that multiple probes of different types are used to measure the ECP and that the highest ECP value is used to assess the HWC-M effectiveness. The NRC staff agrees with this method because the most conservative ECP value is used to assess the HWC-M effectiveness.

For plants with HWC-M, the BWRVIP proposed to use the measured ECP value as a primary parameter and use two continuously monitored secondary parameters (i.e., feedwater hydrogen flow rate or concentration and normalized main steam line radiation) to ensure the availability of HWC-M at the subject location. The BWRVIP stated that a good correlation will be established between the measured ECP value and the secondary parameters so that, in the event of any failure of an ECP probe, the secondary parameters will be used to assess the hydrogen availability at the desired location. The plant will use the ECP data from the ramping test to select the hydrogen injection rate needed to ensure that the ECP value is maintained at or below -230 mV at that location. The NRC staff agrees with this approach because this method ensures adequate HWC-M availability at the desired location when the secondary parameter values are maintained at or below the required threshold levels that correlate to an ECP value of -230 mV. The BWRVIP also proposed to use the BWRVIA model to calculate the total oxidant at the area of interest as a function of feedwater hydrogen concentration. Based on the existing data, the BWRVIP claims that effective HWC-M availability is achieved when the total oxidant content at the area of interest is [Content Deleted - EPRI Proprietary Information less.

The BWRVIP presented data regarding the effect of RCS flow rates on crack growth rates and concluded that at high RCS flow rates the aggressive ions that enhance the corrosion process near the crack tip will be flushed out, thereby reducing the crack growth rate. The NRC staff agrees with the BWRVIP that crack growth rates are increased at low RCS flow rates. Therefore, the NRC staff concludes that a conservative prediction of crack growth rates at the area of interest can be achieved when the BWRVIA model is used to calculate ECP at the low flow rate of [ ]. Based on the review of the data provided in BWRVIP-62, supplemented by the BWRVIP responses, the NRC staff concludes that credit can be claimed for HWC-M when the measured ECP value at the subject location is -230 mV or below, the total calculated oxidant is [ ] or less, and the calculated ECP value at a low RCS flow rate [ ] is equal to or less than -230 mV.

3.3.3.1 ECP Model for Category 1 Plants

For Category 1 plants, when the ECP values cannot be measured at the location of interest, an appropriate BWRVIA model can be used to estimate ECP at this location. Correlation between the measured ECP value and the calculated total oxidant as a function of secondary variables (feedwater hydrogen flow rate or concentration and normalized main steam line radiation) using the BWRVIA is essential in assessing IGSCC mitigation at locations where the ECP cannot be measured. As proposed by the BWRVIP, a minimum concentration of feedwater hydrogen will be established such that the calculated value of the total oxidant is [ ] or less at the location of interest. The NRC staff reviewed the results associated with Category 1 plants and concludes that these plants shall demonstrate that the calculated total oxidant value obtained from the BWRVIA model at the desired location is [ ] or less and the calculated ECP value at a low RCS flow rate [ ] is equal to or less than -230 mV. These calculations shall take into consideration the uncertainties that are associated with the application of the model and the additional margin used to compensate for any depletion of HWC-M at the desired location. For Category 1 plants, the implementation steps that were presented in the BWRVIP supplementary response sent by letter dated December 17, 2004, must be followed to demonstrate that an effective HWC-M is achieved in the RCS water at the desired location.

HWC credit can be claimed for RVIs at all locations (with the exception of lower head region) where the model predicts an ECP value equal to or less than ECP of -230mV or below and a total oxidant of [ ] or less.

As stated in Section 3.2.1 of this SE, the data that was obtained from the [Content Deleted - EPRI Proprietary Information] plants show inconsistencies between the calculated and measured ECP values at the lower head region. Therefore, the NRC staff concludes, as discussed in Section 3.2 that the BWRVIA model requires validation for RVIs in the lower head region, which can be achieved by installing an ECP probe specifically in this region. HWC credit can be claimed for RVIs in the lower head region provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number when the measured value is -230 mV. If the difference in ECP value is a positive number then the calculated ECP value per the BWRVIA model is less conservative. Hence, to use BWRVIA model predictions for HWC credit, adjustment factors must be developed based on a correlation between the measured and calculated (per the BWRVIA model) ECP values. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value.

The NRC staff requests that the BWRVIP provide all available information on inspection results to date (e.g., crack growth rates) for any component that is located in a remote location where ECP values are not measured. This data will be useful in assessing the availability of hydrogen at these locations. The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

3.3.3.2 ECP Model for Category 2 Plants

In its response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that since no ECP is measured for HWC-M Category 2 plants, the BWRVIA model is used to estimate the ECP value and that this value is used as the primary parameter for these plants. These plants shall derive the ECP value based on ECP measurements in a sister plant, if available, and the details regarding sister plants are discussed in Section 3.2 of this SE.

However, if a Category 2 plant (as listed in Table 3-5 of BWRVIP-62) does not have measured ECP data from a sister plant available, then it shall derive a calculated ECP value that is low enough to assure that an ECP of -230 mV or below is achieved for that plant design. The data plotted in Figure 6 of the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, provides a basis for selecting a bounding value for the calculated ECP for a given plant. The BWRVIA model will be used to calculate the total oxidant. If the total oxidant calculated at other plant locations is less than the concentration for the bounding value for the calculated ECP, then effective mitigation is assured at those locations. This may lead to more conservative ECPs for plants with no measured ECP or sister plant ECP data. The BWRVIP proposed to measure at least two secondary parameters (preferably, feedwater hydrogen injection rate or concentration and normalized main steam line radiation) to ensure protection from IGSCC. The BWRVIP further states that additional margin is provided in Category 2 plants by increasing the hydrogen injection rate so that the total oxidant from the BWRVIA model is maintained at [ ] or less and the ECP value at low flow [ ] is maintained at -230 mV or below.

The NRC staff reviewed the BWRVIP response and concludes that, for Category 2 plants with no measured ECP values, HWC-M credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the HWC credit can be claimed at all locations where the model predicts an ECP of -230 mV or below and a total oxidant of [ ] or less. However, an ECP probe must be installed in the lower head region to confirm the model prediction at the next refueling outage. To ensure the validity of the BWRVIA model predictions, the NRC staff expects the BWRVIA model to predict a conservative ECP value. HWC credit can be claimed for RVIs in the lower head regions and other regions provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number when the measured value is -230 mV. Following installation of ECP probe(s), the performance of HWC ramp testing and the development of correlation between measured ECP and secondary parameters, the classification of these plants may be changed from Category 2 to Category 1. If the difference in ECP value is a positive number then the calculated ECP value per the BWRVIA model is less conservative. Hence, to use BWRVIA model predictions for HWC credit, adjustment factors must be developed based on a correlation between the measured and calculated (per the BWRVIA model) ECP values. When multiple valid ECP measurements are available, the most conservative (highest) ECP value should be used to establish the feedwater hydrogen concentration at which IGSCC is mitigated. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value.

Due to inconsistencies between the measured and calculated ECP values for RVIs located in the lower head region, the NRC staff concludes (as discussed in Section 3.2) that the BWRVIA model requires validation for RVIs located in the lower head region. This can be achieved by installing an ECP probe specifically in this region.

The NRC staff requests that the BWRVIP revise BWRVIP-62 to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letter dated December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letter dated December 17, 2004.

3.3.3.3 ECP Model for Category 3a Plants

In its response sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that for NMCA plants (Category 3a), the BWRVIP proposed to measure the ECP value of NMCA treated stainless steel at a given location, and that this measured ECP value will be used as a primary parameter to ensure the effectiveness of NMCA at that location. The ECP probes will be exposed to reactor water and may be located within the vessel, in the bottom head drain, in the reactor water cleanup system or in a recirculation line or in external monitoring stations such as the Mitigation Monitoring Skid that is exposed RCS water from these locations.

A plant must conduct a hydrogen ramping test in order to determine the effect of feedwater hydrogen on ECP and select the feedwater hydrogen operating point. [

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In addition, the BWRVIP proposed to implement continuous monitoring of two secondary parameters (i.e., the measured value of hydrogen-to-oxygen molar ratio and the feedwater hydrogen flow rate or concentration) in order to ensure the availability of NMCA at the subject location. The BWRVIP stated that a good correlation will be established between the measured ECP value and the secondary parameters so that, in the event of any failure of an ECP probe, the secondary parameters will be used to assess the effectiveness of NMCA at the desired location. The NRC staff agrees with the approach of ensuring adequate NMCA availability at the desired location by maintaining the secondary parameter values at the required threshold levels that correlate to maintaining a measured ECP value of -230 mV or below. The BWRVIP stated that a minimum molar ratio of 3 should be maintained at the measured location in order to achieve a molar ratio of 2 throughout the RVI locations. Based on the data provided by the BWRVIP to date, the NRC staff concludes that credit can be claimed for NMCA plants when the measured ECP values of the NMCA treated stainless steel at the monitoring location is -230 mV or below, the hydrogen-to-oxygen molar ratio of 3 or more is maintained at the measured location, and the [Content Deleted - EPRI Proprietary Information].

For Category 3a plants, when the ECP values cannot be measured at the location of interest, an appropriate BWRVIA model can be used to predict the molar ratio at various locations. A predicted molar ratio of 2 or more in non-monitored locations will ensure effective IGSCC mitigation and NMCA for the RVIs.

NMCA credit can be claimed for RVIs at all locations where the BWRVIA model predicts a molar ratio of 2 or more. However, NRC staff approval is required when the licensees intend to take credit for an effective NMCA program when a hydrogen-to-oxygen molar ratio is programmatically maintained below 3.

BWRVIP-62 does not provide sufficient measured ECP data points for the RVIs in the lower head region to demonstrate the validity of the BWRVIA model. Since inconsistencies exist between the calculated and measured ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model by installing an ECP probe specifically in this region as discussed in Section 3.2.

For Category 3a plants, the implementation steps that were presented in the BWRVIP supplementary response sent by letter dated December 17, 2004, must be followed to obtain an effective NMCA in the RCS water. The NRC staff recommends that the BWRVIP provide all information on inspection results (i.e., crack growth rates) available to date for any component that is located in a remote location where ECP values cannot be measured. This data will be useful in assessing the availability of NMCA at these locations.

The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

3.3.3.4 ECP Model for Category 3b Plants

In its response sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that plants in Category 3b use the measured molar ratio and noble metal catalyst loading as primary parameters. Plants will conduct a hydrogen ramping test to determine the effect of feedwater hydrogen on the measured molar ratio target of 3 or more and calculated molar ratio of a minimum value of 2 or more and select the feedwater hydrogen operating point. During the hydrogen ramping test, the plant shall correlate the measured molar ratio with a minimum of two secondary parameters listed in Table 3-5, presented in the BWRVIP supplementary response sent by letter dated December 17, 2004.

The BWRVIA model predicts the molar ratio at various locations within the vessel and piping as a function of feedwater hydrogen. The model prediction for the feedwater hydrogen that is required for a molar ratio of 3 or more shall be compared to and verified with the feedwater hydrogen concentration required for a measured molar ratio of 3 or more. A predicted molar ratio of 2 or more in the non-monitored locations will ensure effective IGSCC mitigation and NMCA.

The NRC staff reviewed the BWRVIP response and concludes that for Category 3b plants with no measured ECP values, NMCA credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the NMCA credit can be claimed at all locations where the model predicts a molar ratio of 2 or more.

However, an ECP probe must be installed to confirm the model prediction at the next refueling outage. The ECP probe will measure ECP of the NMCA treated stainless steel to confirm model prediction for molar ratio. The ECP probe will be exposed to RCS water and may be located within the vessel, in the reactor water clean up system, in a recirculation line, or in external monitoring stations such as the Mitigation Monitoring Skid that is exposed to RCS water. NRC staff concludes that credit can be claimed for NMCA plants when the measured ECP values of the NMCA treated stainless steel at the monitoring location is -230 mV or below, the hydrogen-to-oxygen molar ratio of 3 or more is maintained at the measured location, and the [Content Deleted - EPRI Proprietary Information].

For NMCA plants, BWRVIP-62 does not provide sufficient data for measured ECP to demonstrate the validity of the BWRVIA model for RVIs located in the lower head region. Since inconsistencies exist between measured and calculated ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model for NMCA plants by installing an ECP probe specifically in this region as discussed in Section 3.2.

The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

Table 3-1: Primary and Secondary Parameters to be Used in Implementation of BWRVIP-62 for Category 1, 2, 3a and 3b Plants

Category	Primary Parameters	Secondary Parameters
1. HWC-M	Measured ECP	FW hydrogen flow rate or concentration; Normalized MSLR; MS line oxygen; Reactor water oxygen; Reactor water hydrogen
2. HWC-M (No ECP measurements)	Estimated ECP from Radiolysis/ECP model	FW hydrogen flow rate or concentration; Normalized MSLR; MS line oxygen; Reactor water oxygen; Reactor water hydrogen

3a. NMCA	Catalyst loading and Measured ECP	FW hydrogen flow rate or concentration; Reactor water oxygen; Measured hydrogen-to-oxygen molar ratio; Hydrogen-to-oxygen molar ratio from Radiolysis/ECP model
3b. NMCA (No ECP measurements)	Catalyst loading and Measured hydrogen-to-oxygen molar ratio	FW hydrogen flow rate or concentration; Reactor water oxygen, Hydrogen-to oxygen molar ratio from Radiolysis/ECP model

Key: FW: Feed Water; MSLR: Main Steam Line Radiation; MS: Main Steam

3.4 Technical Basis for Proposed Inspection Credit

Section 4.0 of BWRVIP-62 discusses crack growth rates in stainless steels and Alloy 182 welds for plants that implement HWC-M and/or NMCA. Based on the information provided, the NRC staff agrees that crack growth rates decrease when ECP values decrease (i.e., become more negative). The FOI in crack growth rates is based on the availability of HWC-M and/or NMCA. Table 4-4 of BWRVIP-62 provides extensive information regarding the cracking history of RVIs and the degree of IGSCC mitigation provided by HWC-M and/or NMCA. The NRC staff reviewed the information and concurs that certain RVIs require higher feedwater hydrogen concentrations than others in order to acquire equivalent protection from IGSCC. Based on the FOI in crack growth rates, the BWRVIP proposed submittal of plant-specific revised inspection intervals for RVIs protected by HWC-M or NMCA. The NRC staff will review this submittal as it becomes available. The discussion of crack growth rates in welds with exposure to neutron fluences greater than 5×10^{20} n/cm^2, but equal to or less than 3×10^{21} n/cm^2 is found in Section 3.1.3 of this SE.

4.0 CONCLUSION

The NRC staff has completed its review of BWRVIP-62 and concludes that a revised inspection program can be developed for RVIs based on the FOI for plants that have implemented HWC-M and NMCA. It should be noted that BWRVIP-62 proposes no quantitative revised inspection schedules and indicates this will be done at a later date. Therefore, at this time, the NRC staff makes no finding on the degree of modification justified over current inspection schedules.

For Category 1 plants, the NRC staff concludes that credit can be claimed for the availability of HWC-M at all locations where the BWRVIA model predicts an ECP of -230 mV or below and a total oxidant of [ ] or less. HWC credit can be claimed for RVIs provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number when the measured value is -230 mV. If the difference in ECP value is a positive number then the calculated ECP value per the BWRVIA model is less conservative. Hence, to use BWRVIA model predictions for HWC credit, adjustment factors must be developed based on a correlation between the measured and calculated (per the BWRVIA model) ECP values. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value. Because of inconsistencies between measured and calculated ECP values for RVIs located in the lower head region, the BWRVIA model requires validation for RVIs in the lower head region. Validation of the BWRVIA model can be achieved by installing an ECP probe specifically in this region.

For Category 2 plants with no measured ECP values, HWC-M credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the HWC credit can be claimed at all locations where the model predicts an ECP of -230 mV or below and a total oxidant of [ ] or less.

An ECP probe must be installed to confirm model prediction at the next refueling outage. Following installation of ECP probe(s), the performance of HWC ramp testing and the development of correlation between measured ECP and secondary parameters, the classification of these plants may be changed from Category 2 to Category 1. To ensure the validity of the BWRVIA model predictions, the staff expects the BWRVIA model to predict a conservative ECP value. HWC credit can be claimed for RVIs in the lower head region and other regions provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number when the measured value is -230 mV. If the difference in ECP value is a positive number then the calculated ECP value per the BWRVIA model is less conservative. Hence, to use BWRVIA model predictions for HWC credit, adjustment factors must be developed based on a correlation between the measured and calculated (per the BWRVIA model) ECP values. When multiple valid ECP measurements are available, the most conservative (highest) ECP value should be used to establish the feedwater hydrogen concentration at which IGCSS is mitigated. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value.

Due to inconsistencies between the calculated and measured ECP values for RVIs in the lower head region, the NRC staff concludes, as discussed in Section 3.3.3.1, that the BWRVIA model requires validation for RVIs in the lower head region which can be achieved by installing an ECP probe specifically in this region.

For NMCA plants, a measured hydrogen-to-oxygen molar ratio of 3 or more in lieu of 2 or more is required which provides extra margin in ensuring effectiveness of the NMCA program. NRC staff's approval is required when intending to take credit for an effective NMCA program when a hydrogen-to-oxygen molar ratio is programmatically maintained below 3 at a measured location.

For Category 3a plants, credit can be claimed for the availability of NMCA with a measured hydrogen-to-oxygen molar ratio of 3 or more which provides extra margin in ensuring the effectiveness of NMCA. For Category 3a plants, the NRC staff concludes that the credit can be claimed for the availability of NMCA at all locations where the BWRVIA model predicts a molar ratio of 2.

The BWRVIP stated that a minimum molar ratio of 3 should be maintained at the measured location in order to achieve a molar ratio of 2 throughout the RVI locations. Based on the data provided by the BWRVIP to date, the NRC staff concludes that credit can be claimed for NMCA plants when the measured ECP values of the NMCA treated stainless steel at the monitoring location is -230 mV or below, the hydrogen-to-oxygen molar ratio of 3 or more is maintained at the measured location, and the [Content Deleted - EPRI Proprietary Information].

For NMCA plants, BWRVIP-62 does not provide sufficient measured ECP data points for the RVIs in the lower head region to demonstrate the validity of the BWRVIA model. Since inconsistencies exist between the calculated and measured ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model by installing an ECP probe specifically in this region as discussed in Section 3.2.

For Category 3b plants with no measured ECP values, NMCA credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the NMCA credit can be claimed at all locations where the model predicts a molar ratio of 2 or more.

An ECP probe must be installed to confirm the model prediction at the next refueling outage. The ECP probe will measure ECP of the NMCA treated stainless steel to confirm model prediction for molar ratio. The ECP probe will be exposed to RCS water and may be located within the vessel, in the bottom drain, in the reactor water clean up system, in a recirculation line, or in external monitoring stations such as the Mitigation Monitoring Skid that is exposed to RCS water. NRC staff concludes that credit can be claimed for NMCA plants when the measured ECP values of the NMCA treated stainless steel at the monitoring location is -230 mV or below, the hydrogen-to-oxygen molar ratio of 3 or more is maintained at the measured location, and the [Content Deleted - EPRI Proprietary Information].

BWRVIP-62 does not provide sufficient measured ECP data points for the RVIs in the lower head region to demonstrate the validity of the BWRVIA model. Since inconsistencies exist between the calculated and measured ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model by installing an ECP probe specifically in this region as discussed in Section 3.2.

For the downcomer region, the BWRVIA model (discussed in Section 3.2 of this SE) should take into consideration the effect of radiation on the hydrogen-oxygen recombination reaction. These calculations should take into consideration the uncertainties that are associated with the application of the model.

The NRC staff requests that the BWRVIP provide any available information on the current and previous inspection results (i.e., crack growth rates) of any component that is located in a remote location where ECP values cannot be measured. This data will be useful in assessing the availability of HWC-M or NMCA at these locations. In addition, the growth rates of deep cracks should be monitored to verify that adequate protection is achieved in the deep crack region with effective HWC-M or NMCA.

The BWRVIP has agreed to address the following items in its future submittals.

(1) Review of reports addressed in References 3 and 4 of this SE.

(2) Future additional work on refining the BWRVIA models to reduce the inconsistencies of the calculated ECP values.

(3) Research data on the ECP model that is applicable to the lower plenum region.

The NRC staff reviewed BWRVIP-62 and the associated responses to the Open Items in the NRC staff's initial SE. The NRC staff finds BWRVIP-62, as modified and clarified to incorporate the NRC staff's comments above, acceptable for providing a technical basis for inspection credit for BWR RVIs in Category 1 and 3a plants. BWRVIP-62 also provides an acceptable technical basis for allowing Category 2 and 3b plants to take inspection credit for one operating cycle, until an ECP probe can be installed. As discussed throughout this SE, the modifications that are stated in response to the NRC staff's Open Items must be incorporated in the A-version of BWRVIP-62.

5.0 REFERENCES

1. BWR Vessel and Internals Project, "Evaluation of Crack Growth in BWR Stainless Steel RVIs (BWRVIP-14)," TR-105873NP, March 1996 (ADAMS Accession No. ML003736932 for non-proprietary version sent July 2000).

2. P. Andresen, "Modeling of Water and Material Chemistry Effects on Crack Tip Chemistry and Resulting Crack Growth Kinetics," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Edited by G. Theus, and J. Weeks.

3. T. Yeh, M. Yu, C. Wang, F. Chu, C. Huang, J. Kao, "A Comparative Study of the Effectiveness of Hydrogen Water Chemistry by Computer Modeling for Chinsan and Kuosheng," *Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL 1997.

4. Y. Wada, N Shigenaka, N. Uetake, S. Uchida, "Numerical Simulation of SCC Environment in a BWR Primary Coolant System," *Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL 1997.

5. BWR Vessel and Internals Project, "Modeling Hydrogen Water Chemistry for BWR Applications - New Results (BWRVIP-13)," TR-106068, December 1995 (ADAMS Accession No. ML100890058).

6. J. Strosnider, U.S. Nuclear Regulatory Commission, letter C. Terry, BWR Vessel and Internals Project, "Safety Evaluation of the BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," EPRI Report TR-113932, October 1999, (TAC No. 5012)" September 15, 2000 (ADAMS Accession No. ML003751105).

7. BWR Vessel and Internals Project, "Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," TR-113932, October 1999 (ADAMS Accession No. ML993080249).

Attachment: As stated

Principal Contributor: G. Cheruvenki

Dated:

Attachment 1
Table of Proposed Changes
NRC Draft Safety Evaluation of BWRVIP-62

Item No.	Location in Proposed Revision	BWRVIP Change or Issue	Staff's Disposition
Editorial Comments			
1	1.1, P2, top	Revised to indicate that this SE is the second draft.	Incorporated the comment.
3a	2.0, P3, top	Provided the formal title for the BWRVIA model.	Incorporated the comment.
4	3.1, P4, 1st Para	Indicated that noble metals are on the component surface, not in the surrounding reactor water.	Incorporated the comment.
5a	3.2, P7, 1st Para	Replaced "point" with "plant."	Incorporated the comment.
5c 7c 27	3.2, P7, 1st Para 3.2, P8, 3rd Para 3.4, P19, bottom	Deleted "of the RCS water" after "ECP."	Incorporated the comment.
6	3.2, P8, top	Revised last sentence to reference the BWRVIP submittal of 12/17/04 instead of 8/1/01 and to indicate the revision to BWRVIP-62 Table 3-5.	Incorporated the comment.
7a	3.2, P8, 3rd Para	Inserted "the NRC staff" into first sentence.	Incorporated the comment.
36	3.2, P9, 3rd Para	Changed "lower plenum radiation monitor (LPRM)" to "local power range monitor (LPRM)"	Incorporated the comment.
10	3.2, P10, top	Replace "oxidizing" with "oxidized" stainless steel	Incorporated the comment.
19a	3.3.3.2, P15, 3rd para	Deleted one required measured ECP and total oxidant values.	Incorporated the comment.
Technical Issues			
3b 5b 7b	2.0, P3, top 3.2, P7, 1st Para 3.2, P8, 3rd Para	Use and validation of the BWRVIA Radiolysis and ECP model	Incorporated the comment.
8	3.2, P9, 3rd Para	Deleted "and/or NMCA" from the sentence starting "That is, if credit is desired..."	The staff does not agree with the BWRVIP, and it requires installation of an ECP probe in the reactor lower head. Therefore, "NMCA" is not deleted from the text.
9 17 20 28 29	3.2, P9, 3rd Para 3.3.3.1, P15, top 3.3.3.2, P16, top 4.0, P20, 2nd Para 4.0, P20, 3rd Para	Proposed changes to clarify the requirements for using BWRVIA predictions to demonstrate effective HWC-M.	Incorporated the comment.

11 31a 32	3.3.3.1, P11, 2nd Para 4.0, P20, last para 4.0, P21, top	When molar ratio values are specified, insertions made to indicate whether they apply to "measured" or "BWRVIA calculated" values.	Incorporated the comment.
12 23 31b	3.3.1.1, P12, top 3.3.3.3, P17, 3rd para from top 4.0, P20, last para	Revisions made to clarify the conditions for molar ratio control that would require NRC staff approval for NMCA credit.	Incorporated the comment.
13	3.3.1.4, P12, bottom	The SE incorrectly states the BWRVIP's position in the 8/1/01 submittal on inspection relief for NMCA plants.	Incorporated the comment.
19a	3.3.3.2, P15, 3rd para	Deleted requirement for Category 2 Mod-HWC plants to install a second ECP probe in a location other than the lower vessel head.	Incorporated the comment.
19b 30	3.3.3.2, P16, top 4.0, P20, 3rd Para	Revised to clarify the conditions for Category 2 plants to reclassify to Category 1.	Incorporated the comment.
22	P14, 3.3.3.1, 1st Para 3.3.3.3, P17, 2nd para from top	BWRVIP requests clarification of "appropriate BWRVIA radiolysis model"	Incorporated the comment.
24 26 33 35	3.3.3.3, P17, 4th para from top 3.3.3.4, P18, 5th para 4.0, P21, 3rd Para 4.0, P21, 6th Para	The subject paragraphs require installation of ECP probes in the lower head region of NMCA plants for credit for welds and components in this region.	The staff does not agree with the BWRVIP, and it requires installation of an ECP probe in the reactor lower head.
25 34	3.3.3.4, P18, 3rd para 4.0, P21, 4th Para	The proposed changes reduce the required BWRVIA calculated molar ratio from 3 to 2 for Category 3b NMCA plants, consistent with related paragraphs on NMCA credit in the SE.	Incorporated the comment.

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RECORD OF REVISIONS

Revision Number	Revision
BWRVIP-62	Original Report (TR-108705)
BWRVIP-62-A	This report (BWRVIP-62-A) is based on a previous report (BWRVIP-62) that was reviewed by the U.S. Nuclear Regulatory Commission (NRC). It incorporates changes proposed by BWRVIP in response to NRC Requests for Additional Information, recommendations in the NRC Safety Evaluation, and other necessary revisions identified since the previous publication of the report. All changes, except corrections to typographical errors, are marked with margin bars. Non-essential format changes were made to comply with current EPRI publication Guidelines. In accordance with NRC guidelines, the NRC Safety Evaluation as well as other NRC correspondence related to this report has been included. NRC Safety Evaluation added to Front Matter Appendix A "Physical Explanation of Molar Ratio Prediction of BWRVIA Model" added. Appendices – added: NRC correspondence Details of the revisions are found in Appendix G
BWRVIP-62-A (2018 Update) (3002014434)	Revised report title to BWRVIP-62-A (2018 Update): *BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection*. EPRI, Palo Alto, CA: 2018. 3002014434 and assigned a new EPRI report number Updated the proprietary notice on the title page Incorporated the final NRC Supplemental Safety Evaluation of BWRVIP-62-A. Added the conclusion of the NRC Supplemental Safety Evaluation to the Abstract Replaced the Report Summary with the reformatted and revised Executive Summary to comply with current EPRI publication guidelines and added the conclusion of the Supplemental Safety Evaluation to the Executive Summary

ABSTRACT

Boiling water reactor (BWR) availability has been negatively impacted by the intergranular stress corrosion cracking (IGSCC) of austenitic stainless steel piping and, more recently, reactor internal components. As mandated by Nuclear Regulatory Commission (NRC), regular inspection is necessary for BWR piping to provide adequate assurance of structural integrity of affected piping systems. Similar inspections may be required for reactor internal components. However, due to the difficulty and expense of reactor internals inspections, it is clearly desirable to demonstrate that fewer inspections are necessary when suitable reactor internals IGSCC mitigation steps are taken.

The NRC has agreed that the environmental IGSCC mitigation technique, hydrogen water chemistry (HWC) combined with lower water conductivity provides a basis for inspection relief for BWR recirculation piping (W. Sheron, NRC letter to R. A. Pinelli, BWROG, "Safety Evaluation of Topical Report," NEDE-31951P, dated January 1995). Since the NRC established inspection relief criteria for recirculation piping with HWC, the HWC process has been developed along two parallel paths for mitigation of reactor internals IGSCC. The first qualified HWC technique for reactor internals involves higher hydrogen injection rates than would typically be used to protect recirculation piping. This process is referred as **moderate HWC (HWC-M)** and results in sufficient hydrogen addition to lower ECPs to protective levels in the lower plenum. The second equally protective technique involves the continuous injection of a small amount of hydrogen to give a hydrogen to oxygen molar ratio >2 in the single phase liquid region plus an occasional batch injection of catalytic noble metal compounds. This second process is referred to as **noble metal chemical application (NMCA),** formally known as noble metal chemical addition, and is also known by the GE trademark NobleChem™. Since both processes can protect BWR internals from environmental assisted cracking degradation, the effective implementation of either HWC-M or NMCA implementation at a BWR is a basis for inspection relief for reactor internals.

Based on the crack growth modeling and radiolysis results, a vessel internals inspection program can be developed based on factors of improvement (FOI) for plants that have implemented either HWC-M or NMCA. The FOI calculated for each internal component based on modeling results would be applied to revise the internals inspection interval established in the various BWRVIP I&E documents. BWRVIP will propose revised inspection intervals for vessel internals for plants that have implemented either HWC-M or NMCA at a later date. The NRC concludes that BWRVIP-62-A is acceptable for providing a technical basis for inspection credit for BWR reactor vessel internals (RVIs) in Category 1 (HWC-M) and Category 3a (NMCA) plants. With the NRC's issuance of the Supplemental SE, plants that have implemented OLNC and meet the criteria within Tables 3-5 and 3-8 of BWRVIP-62-A for a Category 3a plant may claim HWC inspection credit in accordance with BWRVIP reports that allow for it (e.g., BWRVIP-41 Rev. 4,

BWRVIP-75-A, BWRVIP-138 Rev. 1-A, and BWRVIP-180) with the knowledge that it is now officially approved by the NRC.

Keywords

BWR, Intergranular stress corrosion cracking, Hydrogen water chemistry, Noble metal chemical application, Reactor internals, Inspection reflief.

EXECUTIVE SUMMARY

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Product Title: BWRVIP-62NP-A (2018 Update): BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection

PRIMARY AUDIENCE: BWR Plant Chemists, Engineers and BWRVIP Program Owners

SECONDARY AUDIENCE: BWR Plant Managers

KEY RESEARCH QUESTION

Boiling water reactor (BWR) availability has been negatively impacted by intergranular stress corrosion cracking (IGSCC) of weld heat affect zone (HAZ) sensitized Type 304/316 stainless steel piping and, more recently, reactor internal components such as the core shroud. Nickel- base alloys such as Alloy 600 and Alloy 182 weld metal have also suffered IGSCC in the BWR environment. BWRVIP inspection and evaluation (I&E) guidelines for reactor vessel piping and internals are in place to ensure continued safe operation through critical monitoring of components' structural integrity. This report reviews the effectiveness of two techniques in mitigating IGSCC of internals: moderate HWC (HWC-M) that uses hydrogen injection rates in the range of 1 to < 2 ppm in the feedwater and noble metal chemical application (NMCA) that uses injection of a smaller amount (0.2 to 0.4 ppm) of hydrogen plus off-line batch injection of a small amount of noble metal compounds that act as catalysts for the recombination reactions.

RESEARCH OVERVIEW

The report describes the requirements for effective implementation of Moderate Hydrogen Water Chemistry (HWC-M) and Noble Metal Chemical Application (NMCA) to mitigate IGSCC in BWRs based on the use of primary and secondary monitoring parameters. The BWRVIA radiolysis/ ECP model is an effective tool to estimate plant water chemistry conditions and ECP at specific component locations. The BWRVIA radiolysis/ECP model results can be used with the BWRVIP empirical stainless steel and nickel-base Alloy 182 weld metal crack growth models to quantify the decrease in crack growth rates with hydrogen injection. This reduction in crack growth rates (factor of improvement) provides the technical basis to develop revised inspection intervals for BWR internals.

KEY FINDINGS

- One of the major problems in demonstrating the effectiveness of HWC-M or NMCA inside the reactor vessel is the difficulty of measuring the electrochemical driving force for IGSCC, i.e., the corrosion potential/electrochemical corrosion potential (ECP), of the various reactor internal components. Furthermore, ECP reference electrodes have only a limited service life before failure and are very costly to replace. Therefore, it is desirable to develop valid supplementary techniques that do not depend exclusively on direct measurement of the ECP at specific locations to reliably demonstrate HWC effectiveness.
- To accomplish this objective, an approach has been developed that can be applied in the absence of direct ECP measurements or as a supplement to direct ECP measurements. For example, ECP can be calculated using verified computer models such as the BWRVIA radiolysis/ECP model that can be directly correlated with measurements of other plant parameters, (e.g., oxygen, main steam line

radiation levels, etc.). ECPs can also be evaluated from electrochemical and chemical measurements obtained from essentially radiolytically and operationally equivalent "sister" plants.

- The BWRVIA radiolysis/ ECP model is an effective tool to estimate plant water chemistry conditions and ECP at specific component locations. The BWRVIA radiolysis/ECP model results can be used with the BWRVIP empirical stainless steel and nickel-base Alloy 182 weld metal crack growth models to quantify the decrease in crack growth rates with hydrogen injection. This reduction in crack growth rates (factor of improvement) provides the technical basis to develop revised inspection intervals for BWR internals.

WHY THIS MATTERS

- The changes proposed by the NRC in the Safety Evaluation of April 21, 2010 as well those proposed by the BWRVIP in response to NRC Requests for Additional Information have been incorporated into the current version of the report (BWRVIP- 62-A). The NRC concludes that BWRVIP-62-A is acceptable for providing a technical basis for inspection credit for BWR reactor vessel internals (RVIs) in Category 1 (HWC-M) and Category 3a (NMCA) plants
- Furthermore, the NRC Supplemental SE of July 6, 2018 concludes that plants that have implemented Online NobleChem™ (OLNC) and meet the criteria within Tables 3-5 and 3-8 of BWRVIP-62-A for a Category 3a NMCA plant may claim HWC inspection credit in accordance with BWRVIP reports that allow for it. With the NRC's issuance of the Supplemental SE, plants that have implemented OLNC and meet the criteria within Tables 3-5 and 3-8 of BWRVIP-62-A for a Category 3a plant may claim HWC inspection credit in accordance with BWRVIP reports that allow for it (e.g., BWRVIP-41 Rev. 4, BWRVIP-75-A, BWRVIP-138 Rev. 1-A, and BWRVIP-180) with the knowledge that it is now officially approved by the NRC.

HOW TO APPLY RESULTS

The approach described in this report can be used for effective implementation of HWC-M or NMCA or OLNC to mitigate IGSCC in BWR internals. Guidance on inspection intervals is provided in BWRVIP Inspection and Flaw Evaluation Guidelines for specific BWR internals and stainless steel piping welds for plants that have effectively implemented these mitigation methods. In the future this guidance will be extended to other internals that are effectively mitigated.

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PROGRAM: BWRVIP, 41.01.03

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INTRODUCTION AND BACKGROUND

1.1 Brief Review of Stress Corrosion Cracking in BWR Piping and Internals

Boiling water reactor (BWR) availability has been negatively impacted by intergranular stress corrosion cracking (IGSCC) of weld heat affect zone (HAZ) sensitized Type 304/316 stainless steel piping and, more recently, reactor internal components such as the core shroud. Nickel-base alloys such as Alloy 600 and Alloy 182 weld metal have also suffered IGSCC in the BWR environment. Table 1-1 and Figure 1-1 summarize the components that have suffered IGSCC in the BWR (1-1, 1-2). As the BWR fleet ages, another form of intergranular environmentally assisted cracking has occurred in highly irradiated non-thermally sensitized stainless steel reactor internal components, i.e., irradiation assisted stress corrosion cracking (IASCC).

Table 1-1
Evolution of IGSCC in the BWR (1-1)

Event	Time of detection
Stainless Steel Fuel Cladding IGSCC	Late 1950s and Early 1960s
IGSCC of 304 During Construction	Late 1960s
IGSCC of Furnace Sensitized Type 304 During Operation	Late 1960s
IGSCC of Welded Small Diameter Stainless Steel Piping	Mid 1970s
IGSCC of Large Diameter 304 Piping	Late 1970s
IGSCC of Alloy X750 Jet Pump Beam	Late 1970s
IGSCC of Alloy 182/600 in Nozzles	Late 1970s
Crevice-induced Cracking of 304L/316L	Mid 1980s
Localized Cold Work Initiates IGSCC in Resistant Material	1980s
Accelerating Occurrence of IGSCC of BWR Internals	Late 1970s
Core Spray Spargers	
Shroud Head Bolts (Alloy 600)	
Access Hold Covers (Alloy 182/600)	
Nozzle Butters	
Control Blades	
SRM/IRM Dry Tube Cracking	
Jet Pump Beam Bolts	

Table 1-1
Evolution of IGSCC in the BWR (1-1) (continued)

Event	Time of Detection
Cracking of Low Carbon (304L/316L) and Stabilized Stainless Steels (347/321/348) In Vessel Locations Core Spray Jumpers Creviced Safe Ends Shrouds (304L and 347) Top Guide (304, 304L, 347) Core Support Plate (347)	Late 1980s – present
Cracking of Internal Core Spray Piping	1980s – present

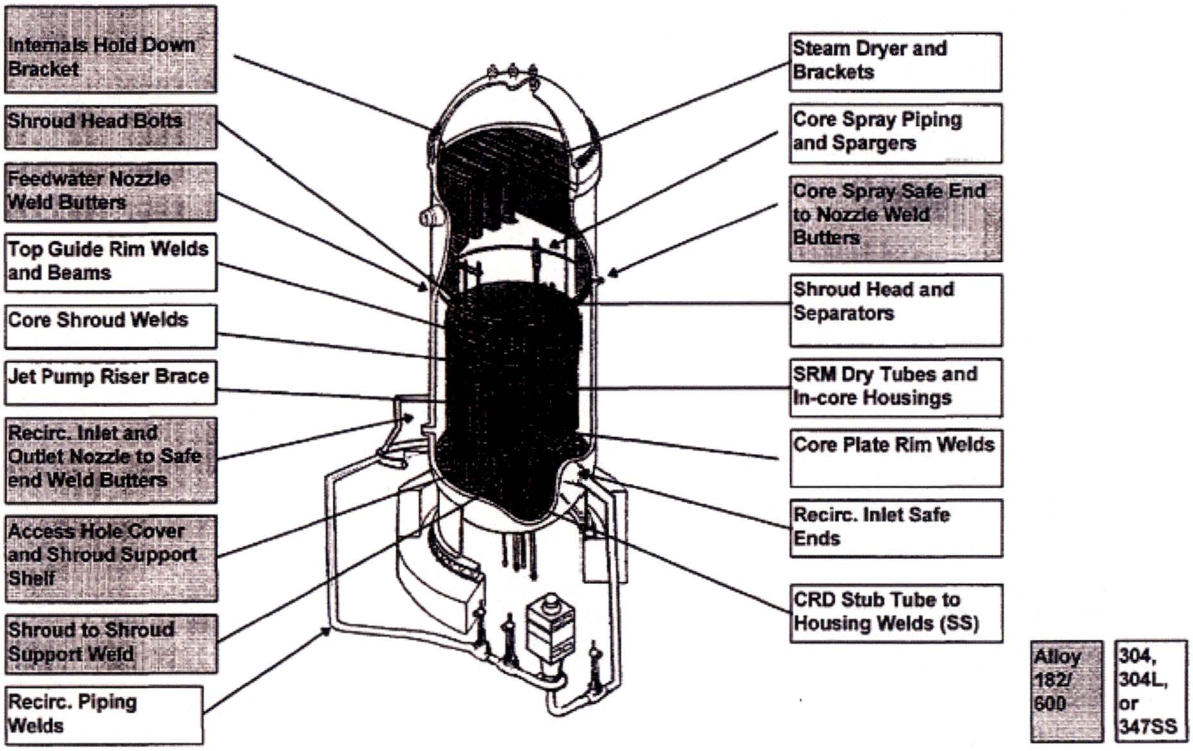

Figure 1-1
Summary Schematic of Components Indicating IGSCC in the BWR (1-2)

The first significant occurrence of IGSCC of welded Type 304 stainless steel BWR piping occurred in the fall of 1974 and early 1975 (1-3). Sixty-four (64) incidents of cracking were identified in weld HAZs during this period, all of which occurred in small diameter pipes (<25.4 cm [<1 0 in.]). In fact, most of the cracks were found in 10.2 cm (4 in.) diameter recirculation bypass lines. Although these cracking incidents were not (and are not) considered safety concerns, they did significantly impact BWR availability, operating costs and person-Rem exposure for inspection, repair, etc. During 1978, incidents of IGSCC were first noticed in large diameter (61 cm [24 in.]) piping in the German reactor, KRB (1-4). This incident established additional concern for the main recirculation piping in all BWRs with Types 304 and 316 stainless steel piping, since replacement of these large diameter lines would be more difficult and costly.

To date, only creviced Alloy 600 has suffered IGSCC in the BWR. In fact, no uncreviced Alloy 600 IGSCC has been identified in the field. (Uncreviced Alloy 600 cracks in laboratory simulated BWR environments.) The first field incident of creviced Alloy 600 IGSCC occurred at Duane Arnold BWR in creviced reactor vessel nozzle safe ends in 1978 after approximately three (3) years of operation. The premature cracking of the safe ends was due to a synergistic combination of a severe (~360 kg [800 lbs.]) resin intrusion (high sulfate) during startup (1-5) and the highest stress state design of any BWR recirculation inlet safe ends in the fleet. Subsequent to this incident, other creviced nickel-base alloy nozzle safe ends plus reactor internals components such as creviced shroud head bolts (SHBs) and creviced access hole covers (AHCs) have suffered IGSCC. All the cracking in these creviced components was determined to be directly related to the respective plant's conductivity, i.e., the higher the reactor water conductivity, the earlier the IGSCC. Alloy 182 weld metal has also experienced IGSCC in uncreviced nozzle safe end applications where weld residual stresses and fairly high-applied stresses were present. Additionally, since there have been a few reported instances of Alloy 182 IGSCC in components with weld residual stresses and low applied stresses, (e.g., top head lugs, shroud support, etc.), it must be conservatively assumed that welded Alloy 182 exposed to normal coolant conditions can develop IGSCC even in areas of low applied stresses.

IGSCC of irradiated annealed non-sensitized stainless steel, i.e., IASCC, was first observed in 1959 in Type 304 stainless steel fuel cladding (1-4). (This early corrosion concern motivated the introduction of zirconium alloys for BWR fuel cladding.) Two years later, IGSCC of irradiated boron alloy stainless steel control blades was identified. (Control blades containing B4C pellets inside stainless steel tubes replaced these control blades.) Initially IASCC, as it is now distinguished from thermally sensitized material, was only identified in readily replaceable components such as control rods, control blade handles, neutron source holders, dry tubes, intermediate and source range monitors, and various bolts and springs. Since these components are readily replaceable and many of the components are replaced routinely for other reasons, IASCC of these components did not have a significant impact. However, in 1990, the first confirmed IASCC of a lower carbon (0.045 %) Type 304 stainless steel shroud was identified at KKM in Switzerland (1-6). (The IASCC cracking mechanism was justified due to the total lack of thermal sensitization, lower carbon content and high fluence [8 to 12 x 10^{20} n/cm^2].)

Since 1990, many core shrouds have been inspected and typical weld sensitization HAZ IGSCC characterizes most shrouds (1-6). Cold work and IASCC have also contributed to some shroud environmental cracking. Shrouds fabricated from Type 304L and Type 347 stainless steel have also suffered cracking. Shroud cracking is now the major environmental cracking concern in the operating BWR.

Thus, the majority of IGSCC in austenitic stainless steels has progressed from the piping systems and nozzle safe ends to the vessel interior, affecting the core shroud and core support structure. The level of activity within the industry to address IGSCC of BWR internals was particularly accelerated by the cracking observed in the HAZ of circumferential shroud welds at Brunswick Unit 1 in 1993 (1-6). The IGSCC observed at Brunswick was most severe in the HAZ of the top guide support ring portion of the shroud. A mechanical repair was performed and the unit was returned to service. Subsequent inspections at other BWR utilities revealed cracking of varying severity at essentially all of the core shroud's stainless steel horizontal weld joints. In addition, cracking has been observed in the vertical stainless steel core shroud weld HAZs in some BWRs. The severity of the core shroud cracking has been correlated with the following parameters: (1) hot operating time in "on-line years," (2) first five cycles mean conductivity of the reactor water, (3) materials of construction and (4) neutron fluence. Repair/restraint techniques have been developed to allow BWR utilities to manage the core shroud cracking of both horizontal and vertical welds.

In addition to core shroud IGSCC/IASCC, cracking was visually identified in a stainless steel top guide in 1991 at the Oyster Creek BWR. Since the sample removed from the top guide has only been examined by eddy current and as yet, has not been metallugically evaluated, the exact cause of cracking is unknown. However, IASCC is the leading candidate.

Finally, IGSCC has also been observed in older Alloy X-750 jet pump hold-down beams and brackets that were not manufactured with the optimal IGSCC resistant heat treatment (1-4).

Some initial evidence of IGSCC has been also observed in steam dryer hold down brackets welded with Alloy 182.

1.2 Role of Ionic Impurities in the BWR Coolant

The importance of the BWR environment in the IGSCC process is well-documented (1-1). Statistical analyses of IGSCC cracking trends of especially creviced components have shown that the reactor water conductivity history in a given reactor is a useful indicator of the relative probability of the time to detectable cracking in a component when compared to like components in other reactors (1-7). Research has demonstrated very clearly that the fundamentally important chemistry parameter is the thermodynamic activity of strong acid anions such as chloride and sulfate that are stable in the highly reducing crack tip environment (1-8). These anions are drawn into the crack by the potential difference between the crack tip and mouth, and depress the crack tip pH. Laboratory studies have demonstrated that these impurities accelerate the initiation of IGSCC and promote high crack growth rates. Other anions such as chromate and nitrate that are not stable under reducing conditions have only a minimal effect on IGSCC. Cations such as sodium also appear to have minimal effect, while zinc in some testing has reduced crack growth rate. All ions in the water contribute to the coolant's conductivity, which is the parameter that historically has been continuously monitored and reported. Aggressive anions such as chloride and, more recently, sulfate, are also monitored and reported. High values of conductivity, such as those experienced in earlier years, typically correlated with high concentrations of aggressive anions. Guidelines have been issued addressing the control of BWR water chemistry (1-1). As shown in Figure 1-2, fleet reactor water chemistry as indicated by conductivity has improved significantly (1-1). For example, as early as 1995, the BWR fleet average was just slightly above Content Deleted - EPRI Proprietary Information , close to that of theoretically pure water (0.055 µS/cm). At these low values, the primary contributors to conductivity are not chloride and sulfate, but rather soluble corrosion products such as chromate, non-aggressive impurities such as sodium and nitrate, or beneficial chemical additives such as zinc. Under these conditions, crack growth rate is expected to correlate more strongly with the concentration of aggressive anions than with conductivity.

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EPRI Proprietary Information

Figure 1-2
BWR Mean Reactor Water Conductivity History (1-1)

However, even theoretically pure water will not provide immunity to IGSCC in the BWR. The IGSCC behavior for shroud head bolts, Figure 1-3, shows that although good water quality delays initiation, IGSCC eventually will still initiate (1-1). New cracks were found after approximately 16 years of on-line service in a plant with good lifetime conductivity in this creviced Alloy 600 component. Recently, internals cracking has been reported in an overseas BWR characterized by a lifetime reactor water conductivity average of Content Deleted - EPRI Proprietary Information during its hot operating years. Despite the good water quality, this plant has exhibited extensive cracking in shroud, top guide, and core plate components, all fabricated from "sensitization resistant" stabilized Type 347 stainless steel. (However, metallurgical analysis of this plant did show that the Type 347 stainless steel was sensitized with a marginal niobium to carbon ratio with a 600°C [1112°F] stabilization heat treatment.)

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Figure 1-3
IGSCC Behavior of Alloy 600 Shroud Head Bolts (1-1)

1.3 Role of Oxidizing Environment in the BWR

Early measurements of the chemical makeup of the normal water chemistry (NWC) BWR environment showed that it was characterized by the presence of approximately 200 ppb O_2 and substoichiometric hydrogen (~10 to 20 ppb) due to the radiolytic decomposition of water in the core region. However, subsequent measurement and understanding, developed since the late 1980s, have shown that the environment in the vessel is different to that observed in these earlier sample line measurements. In fact, radiolysis modeling predicts that hydrogen peroxide is the major oxidizing constituent formed in the BWR vessel (1-1). Model calculations typically predict hydrogen peroxide (H_2O_2) concentrations of Content Deleted - EPRI Proprietary Information. However, other model calculations predict hydrogen peroxide concentrations up to Content Deleted - EPRI Proprietary Information.

The corrosion potential or the more commonly called electrochemical corrosion potential (ECP) (These two terms are used interchangeably in this report.) is a thermodynamic measure of the oxidizing power of a solution in contact with a very specific metal surface. The ECP of a component is measured with respect to a reference electrode. Platinum is used in the case of excess, i.e., greater than stoichiometric, hydrogen in the coolant such as would exist with HWC. An iron/iron oxide (Fe/Fe_3O_4) electrode can be used over the entire range of water chemistries (NWC to HWC). From the measured value ΔVm, i.e., the potential difference between the reference electrode and the working electrode (BWR component surface), and the electrode potential of the reference electrode, Eref, relative to the standard hydrogen electrode, SHE, the ECP of the component can be calculated with the following equation:

$$\mathrm{ECP} = E_{ref} - \Delta V_m \quad \text{(mV)}$$

As discussed in Section 1.3, the ECP is the electrochemical driving force for IGSCC. For this phenomenon, the higher, i.e., more positive the ECP, the greater the thermodynamic tendency for crack initiation and growth in susceptible materials stressed above threshold tensile stress levels.

Laboratory measurements indicate that H_2O_2 is significantly more oxidizing than O_2 as reflected by ECP measurements (1-1). Recent studies show that the ECP of stainless steel is 200 mV higher in 400 ppb H_2O_2 than in water with an equivalent concentration of O_2. Measurements of the ECP made in-vessel confirm the high oxidizing corrosion potentials that can be accounted for only by the presence of high concentrations of H_2O_2.

1.4 Effect of Flow Rate on Corrosion Potential and Crack Growth

Mixed potential theory predicts that increasing fluid flow rates result in an increase in corrosion potential or ECP (1-9). This has been confirmed by laboratory testing using rotating cylinder electrodes and by observation of the effects of flow rate on ECP electrodes installed in power plants (1-10, 1-11). Increasing the flow rate decreases the thickness of the stagnant liquid boundary layer present at all wetted metal surfaces. As this boundary layer thickness decreases, the flux of oxidizing species increases. This causes the corrosion potential to increase.

For the BWR, the magnitude of the effect is greatest in certain regimes involving relatively low dissolved oxygen or hydrogen peroxide concentrations. For example, the ECP of stainless steel in water containing about 2 to 5 ppb dissolved oxygen can increase from below the IGSCC initiation threshold ECP of −230 mV(SHE), (e.g.,<-400 mV[SHE]), under low flow conditions to more than 0 mV(SHE) at high flow rates (1-12). ECP measurements obtained from the Quad Cities-2 recirculation system exposed to a flow of Content Deleted - EPRI Proprietary Information showed a potential approximately Content Deleted - EPRI Proprietary Information higher (more positive) than one at a low flow rate of Content Deleted - EPRI Proprietary Information over a range of hydrogen addition rates (1-11).

ECP changes due to flow rate have no affect on crack growth rate. Theory predicted and experimental studies confirmed that the ECP relevant to stress corrosion crack advance is that potential that is established at low flow rate (1-13). This can be understood in terms of the factors that cause aggressive anions to concentrate at the crack tip. Where water is flowing, fluid convection causes impurities to be well mixed. Where there is no flow, anions can be transported through the stagnant water by two processes. They will naturally diffuse from regions of high concentration to low concentration. They will also be moved by electric fields. The ECP establishes an electric field that draws aggressive anions into the crack, causing them to concentrate. However, fluid convection eliminates differences in concentration. If the fluid in the crack begins to flow, impurities will be flushed out. Although electric fields may exist as a result of the ECP, fluid convection will overwhelm their effect on ion transport. Therefore, only the ECP that exists in the stagnant fluid in the crack can cause anions to concentrate in the crack.

Since the ion migration (and diffusion) terms are overwhelmed by convection, then, from a mass transport perspective, two options exist:

1. *Beneficial Effect of Flow*: If the flow rate is sufficiently high and properly oriented to the crack to cause flushing of the crack tip region, then stress corrosion crack growth rates are low because an aggressive crevice/crack chemistry cannot be sustained.
2. *No Effect of Flow*: If the flow rate and crack geometry is such that convective flow subsides at a point half way into the crack, for example, then this point represents the location of the "electrochemical crack mouth". It is the location where the contribution of the potential gradient can strongly influence mass transport and the crack chemistry. At locations toward the geometric crack mouth, any effect of the potential gradient is overwhelmed by convection. Thus, while the corrosion potential at the free surface may be greatly elevated under high flow rate conditions, the flow merely acts to shift the "electrochemical crack mouth" deeper into the crack.

Recently, BWRVIP conducted a project to specifically evaluate the effect of flow rate on ECP and IGSCC initiation and propagation (1-12). Constant extension rate technique (CERT) tests showed that although ECP increased under high flow conditions, there was no negative effect of high flow on crack initiation. For example, Figure 1-4 indicates that the ECP increased with dissolved oxygen as well as flow velocity. ECP increased by approximately **Content Deleted - EPRI Proprietary Information** when the flow was increased from **Content Deleted - EPRI Proprietary Information**. However, high flow velocity had a beneficial effect on crack initiation in spite of the increase in ECP. This is apparent from Figure 1-5 that indicates that the time to cracking increased as the flow rate was increased over the same flow range.

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Figure 1-4
ECP vs. Dissolved Oxygen at Low and High Flow Velocities (1-12)

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Figure 1-5
Influence of Dissolved Oxygen and Time to Failure at Low and High Velocities with the New Specimen Configuration (1-12)

The effect of flow rate on crack propagation was evaluated with cylindrical bar specimens with a circumferential crack in 282°C (540°F) water containing Content Deleted - EPRI Proprietary Information dissolved oxygen (Table 1-2). These tests showed a four-fold reduction in crack growth rate when the flow rate was increased from Content Deleted - EPRI Proprietary Information .The effect was reversible when flow rate was reduced. This supports the hypothesis that high flow rates do not increase and may decrease crack growth rates. In low oxygen water (Content Deleted - EPRI Proprietary Information oxygen) high flow increased ECP but had no significant effect on crack growth. Consistent with trends shown in Figures 1-4 and 1-5, the ECP measured at low flow rates was approximately Content Deleted - EPRI Proprietary Information lower, i.e., apparently less oxidizing, than the ECP measured at higher flow rates. The crack growth rate at higher flow rates is significantly less than the crack growth rate at lower flow rates.

Table 1-2
Effect of Flow Rate on IGSCC Growth Rate and ECP – Type 304 Stainless Steel Bar in 250 ppb Oxygen (1-12)

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The BWRVIP study indicates that since high flow has a mildly or strongly beneficial effect on crack growth it is inappropriate to use the high flow ECP to estimate crack growth. It is therefore more reasonable to use the low flow ECP to estimate crack growth because the crack growth rate under low flow conditions is either similar to or higher than that under high flow conditions. In other words, increasing the flow will not increase crack propagation rate, and depending on the crack geometry and orientation to the flow, may reduce the crack growth rate.

The results of the project are documented in BWRVIP-64 (1-12), which was submitted to the NRC for information only in response to a request for additional information (Open Item 3.2.2). The NRC concluded that the above discussion provided a reasonable explanation of the effect of flow rate on ECP and crack growth rates.

1.5 Role of Irradiation

As noted in Section 1.1 and detailed in EPRI TR-107159, IASCC has become a critical concern for core internals in light-water reactors (LWRs) (1-14). IASCC results from a complex sequence of events involving radiation-induced changes in the metal, component stress, and the in-vessel aqueous environment.

IASCC of stainless steel internals results from an interaction of irradiation, material, environment, temperature and stress. The complexity of the IASCC process stems from the fact that the primary controlling variables are not independent of one another. For example, irradiation can affect the material microstructure and microchemistry, the aggressiveness of the reactor internals environment through water radiolysis, component temperature through gamma heating, and component stresses through radiation hardening and creep relaxation. Further, all the complexities of SCC under unirradiated conditions must also be considered since irradiation effects are believed to promote classical SCC and do not represent a unique cracking phenomenon (1-14).

Susceptibility to IASCC in annealed austenitic stainless steels becomes pronounced at a fluence of approximately 5 x 10^{20} n/cm^2 or ~0.7 displacements per atom (dpa) in BWR environments. Conversely, a higher fluence (~2 x 10^{21} n/cm^2) is required for cracking in low corrosion potential environments, e.g., pressurized-water reactors (PWRs) or BWRs with "good" hydrogen water chemistry. This IASCC "threshold" fluence range (0.7 to 3 dpa) is where many radiation-induced variables change dramatically, so that it has been difficult to isolate individual contributions to the cracking process.

1.6 IGSCC/IASCC Mitigation with HWC

1.6.1 Effect of ECP on IGSCC

Since the oxidizing nature of the environment in the BWR vessel is a key factor in the occurrence of IGSCC, an obvious mitigation strategy is to modify the environment. This approach was attempted in the U.S. and Sweden in the early 1980s. Independently, researchers in both countries concluded that feedwater hydrogen injection could reduce the oxidizing power of the environment and mitigate IGSCC in recirculation piping. Testing at Oskarshamn 1 in 1981 and Dresden 2 in 1982 showed that this concept was indeed practical. CERT tests run in an autoclave installed at Dresden 2 fed by water from the recirculation system clearly demonstrated IGSCC under conditions of no hydrogen injection, but no IGSCC under feedwater hydrogen injection, i.e., low ECP, conditions (1-15).The effect of ECP on IGSCC initiation in stainless steel from various BWRs is shown in Figure 1-6 (1-16). No IGSCC is observed in CERT tests when the corrosion potential of the stainless steel is below −230 mV (SHE). IGSCC initiation is observed in sensitized stainless steel when the ECP is above −230 mV (SHE) even in very pure, low conductivity reactor water.

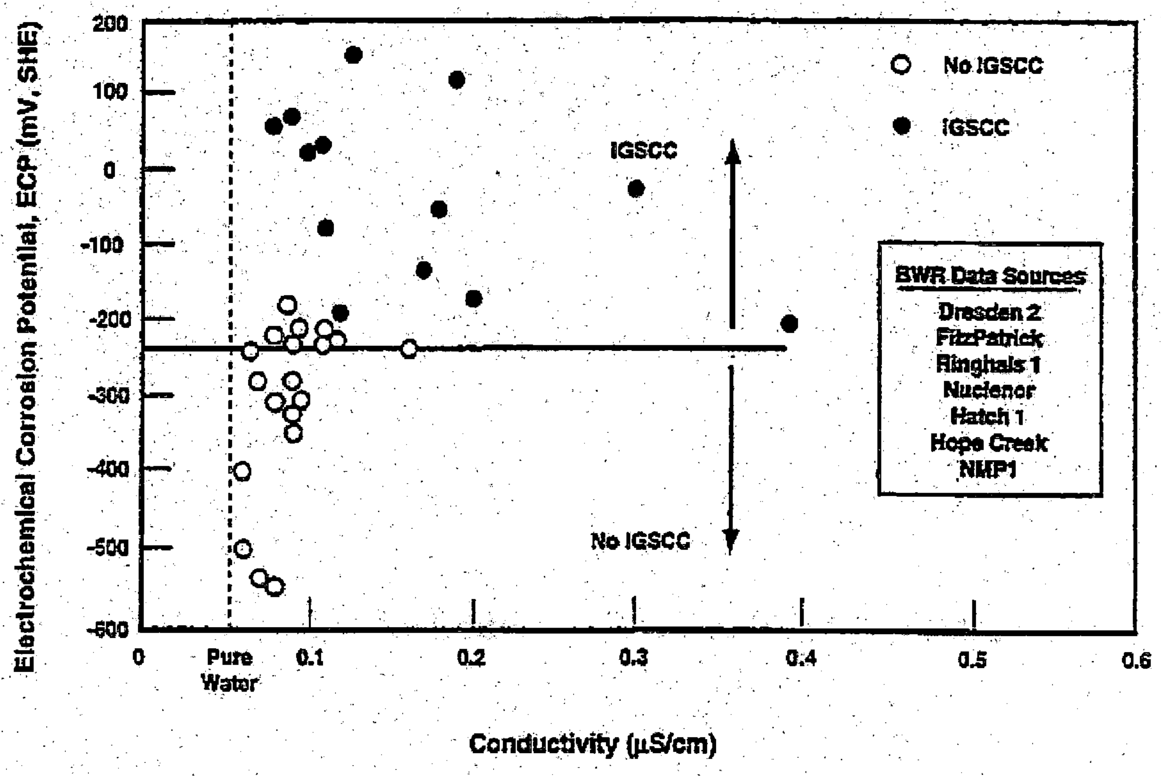
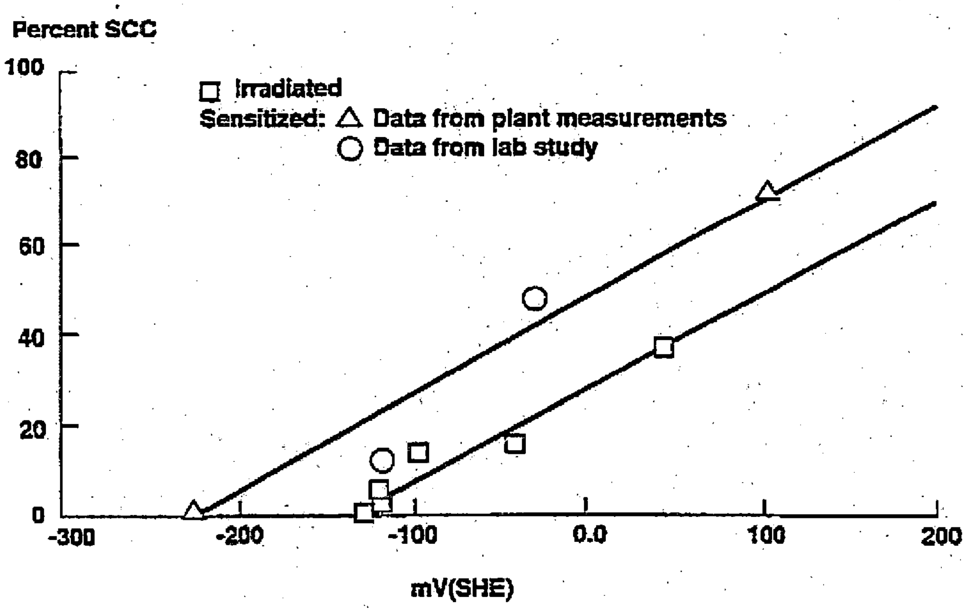


Figure 1-6
CERT Results Supporting IGSCC Protection Potential (1-16)

Figure 1-7 presents results from CERT tests on both thermally sensitized and annealed then irradiated Type 304 stainless steel specimens (1-17). Although this study suggests that the ECP threshold for IGSCC initiation in annealed then irradiated Type 304 stainless steel may be as high as -140 mV (SHE), the data are limited. In addition, the threshold potential may be a function of irradiation level, impurity concentrations and the microstructure and composition of the material. The target threshold ECP for IGSCC initiation will remain less than or equal to −230 mV(SHE) for irradiated stainless steels pending the development of additional data.

Notes: **Percent SCC is % Intergranular Fracture**
Irradiated is solution annealed + irradiated to 1.9 x 10^{21} n/cm^2
Sensitized = Thermally sensitized



Test Environment
Conductivity <0.1 μS/cm
T=274° C
ECP controlled by addition of oxygen

Figure 1-7
Initiation of SCC of Type 304 Stainless Steel as A Function of ECP (1-17)

HWC has also been demonstrated to be quite beneficial to IGSCC initiation in nickel base alloys. Figures 1-8 and 1-9 present results of IGSCC initiation tests performed on modified (U-notch) compact tension specimens exposed in an actual BWR recirculation environment conditions in a Swedish BWR (1-18). Figure 1-8 presents the results of testing in the normal water environment (NWC) on several heats of Alloy 182 weld metal. Figure 1-9 presents the results obtained in a HWC environment on the same materials. Those figures demonstrate that specimens from four of the six heats cracked in the NWC environment, but no cracking was observed in the HWC environment. The specimens cracked in the NWC tests in times as short as effective full power hours Content Deleted - EPRI Proprietary Information whereas the HWC tests exhibited no crack initiation in times greater than Content Deleted - EPRI Proprietary Information .

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Figure 1-8
Alloy 182 Specimens Installed in NWC Verified Results (1-18)

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Figure 1-9
Alloy 182 Specimens Installed in HWC Inspection Result after ≈ 25000 EFPH (1-18)

Crack propagation by IGSCC is also sensitive to the ECP. Figure 1-10 presents crack growth data from autoclaves at BWR sites (1-1). The crack propagation rate of Type 304 stainless steel fracture mechanics specimen is shown for low ECP conditions (established by HWC) and for high ECP conditions (established during NWC). The crack propagation rate increased by a factor of approximately at the higher ECP. The BWRVIP crack growth model lines are also presented in Figure 1-10.

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Figure 1-10
Type 304 Stainless Steel Crack Growth Rate vs. ECP for BWRVIP Model (1-1)

Finally, it should be noted that because each plant is unique in its response to feedwater hydrogen injection, a plant specific HWC-M specification should be established to mitigate IGSCC for asset protection based on the region to be protected. The ECP goal can either be the −230 mV(SHE) for no new crack initiation or a target ECP based on maintaining a minimum target crack growth rate utilizing information from a source such as that used to construct Figure 1-11 (1-1, 1-16). However, for inspection relief, the target threshold ECP for IGSCC mitigation is less than or equal to −230 mV(SHE).

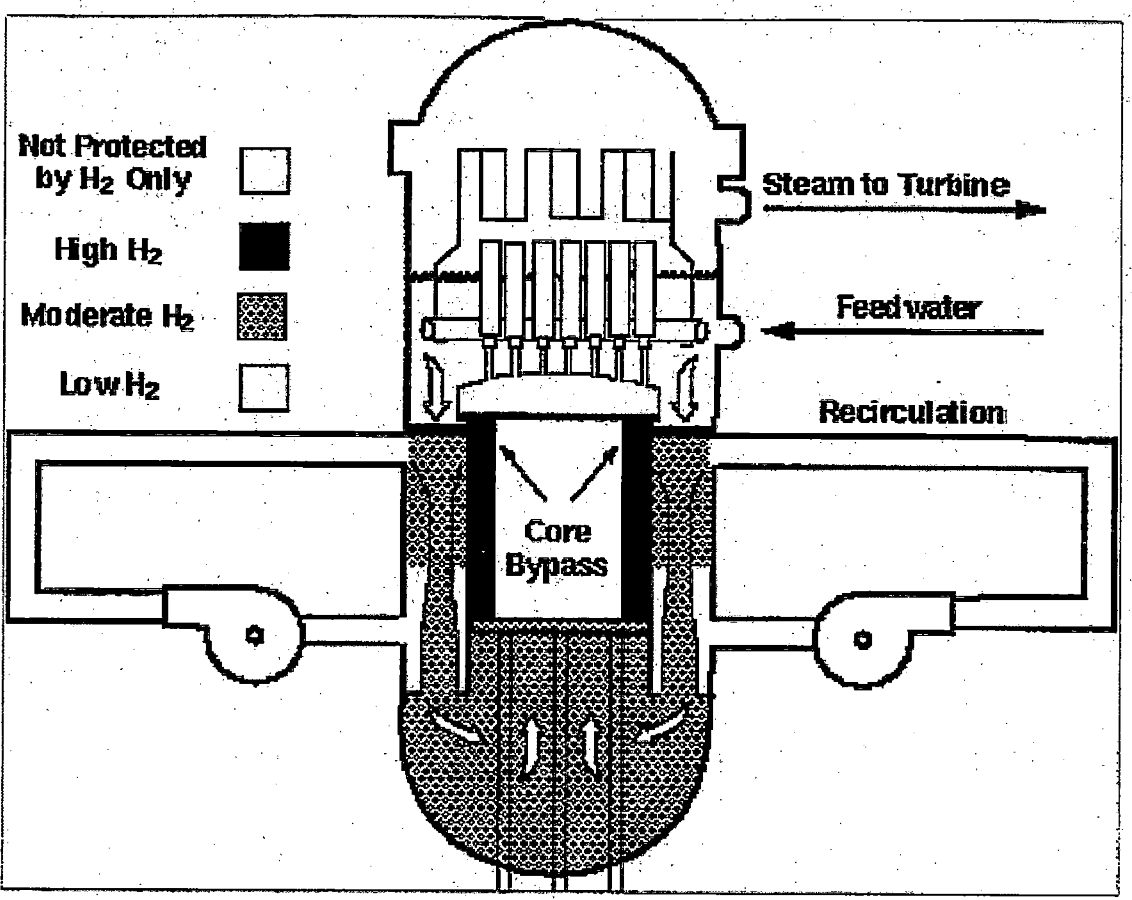

Figure 1-11
Schematic of the BWR Showing the Ranges of Feedwater Hydrogen Required for Reaching −230 mV(SHE) (1-1, 1-16)

1.6.2 Effect of Oxidant Concentration on IGSCC

Slow strain rate (1-23) and crack propagation tests (1-12) show that IGSCC of sensitized stainless steel will be mitigated when the oxidant concentration decreases to 1 to 3 ppb. For example no IGSCC was observed in laboratory slow strain rate tests when the oxygen concentration was decreased from 200 ppb to a range of 1-5 ppb (1-23, Table 2-4). Similarly, reactor slow strain rate tests in Dresden-2 showed no IGSCC when the oxygen concentration was reduced from 270 ppb to the range of 3-30 ppb by adding hydrogen (1-23, Table 2-6). Crack propagation tests on round bar specimens of sensitized stainless steel at low flow rates showed mitigation of crack growth when the oxygen concentration was decreased from 250 ppb to a range of 1-3.5 ppb (1-12, Tables 4-2 and 4-3). These data confirm that IGSCC initiation and propagation will be mitigated at a location if the total oxidant concentration is reduced to 3 ppb or less. The ECP in these low oxygen tests was <−230 mV SHE.

1.7 IGSCC/IASCC Mitigation with NMCA

The primary detrimental side effect of HWC-M is the increase in main steam line radiation (MSLR) levels. The radiation is due to the presence of short-lived water activation products, primarily N-16, that are produced in the core. As the coolant becomes less oxidizing, the chemical form of N-16 shifts from primarily nitrate, which is non-volatile, to more volatile forms such as nitrogen oxides and ammonia. Under the reducing conditions produced by HWC-M, more of the N-16 partitions to the steam. For some plants, the hydrogen injection rate required to protect reactor vessel internals will cause steam activity levels that result in excessive operational exposures and unacceptable radiation levels outside the plant from direct radiation and sky shine. Noble metal chemical application (NMCA) provides a method for achieving the IGSCC protection of HWC-M without affecting N-16 transport and main steam line radiation levels (1-19).

Very simply, noble metals such as platinum, palladium and rhodium catalyze the recombination of oxygen and hydrogen peroxide with hydrogen. When noble metals are applied to a surface, and an excess from stoichiometric amount of hydrogen is added to the coolant, their catalytic action removes all of the oxygen at the surface, thus allowing the protection of reactor internal components with lower levels of hydrogen injection. Consequently, hydrogen feed rates with NMCA will be substantially lower than with HWC-M. Figure 1-12 illustrates the relative reactive nature of stainless steel and noble metal surfaces for reducing the ECP (1-19). When the molar ratio of hydrogen to oxygen reaches 2:1, the ECP dramatically decreases to below IGSCC threshold values.

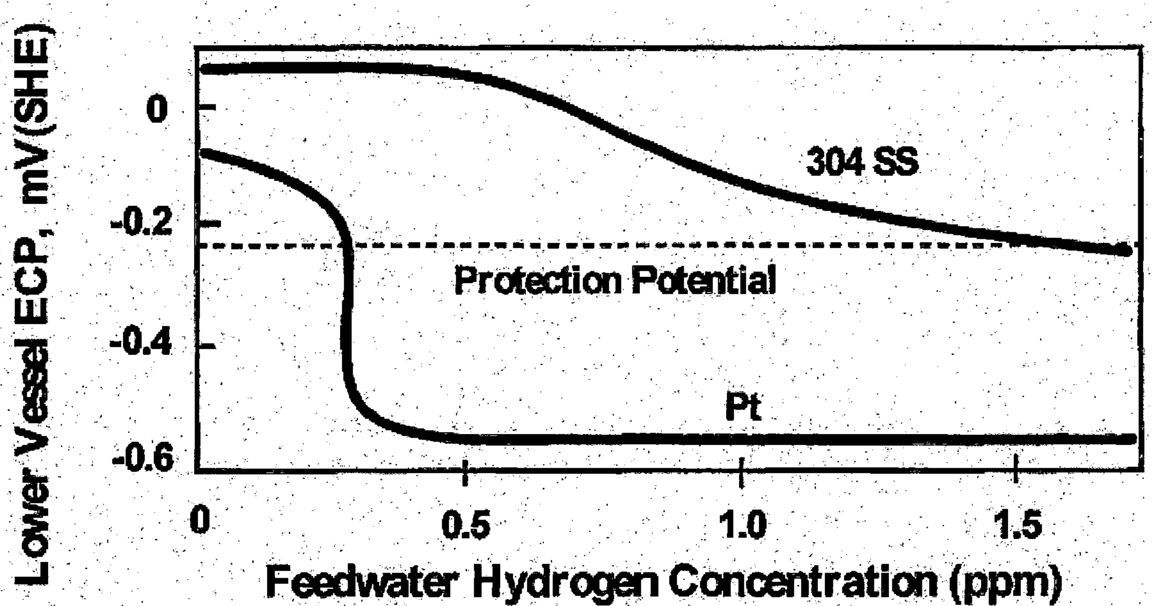

Figure 1-12
Comparison of ECP for Type 304 Stainless Steel and Platinum Surfaces as A Function of Feedwater Hydrogen Concentration (1-19)

This method consists of injecting a solution of suitable noble metal compounds into the reactor water, with subsequent deposition of sufficient noble metal on the material surface to catalytically reduce the ECP in the presence of low hydrogen concentrations. This technique has the advantage of providing IGSCC protection at low hydrogen injection rates with little increase in plant operating dose rates, Figure 1-13.

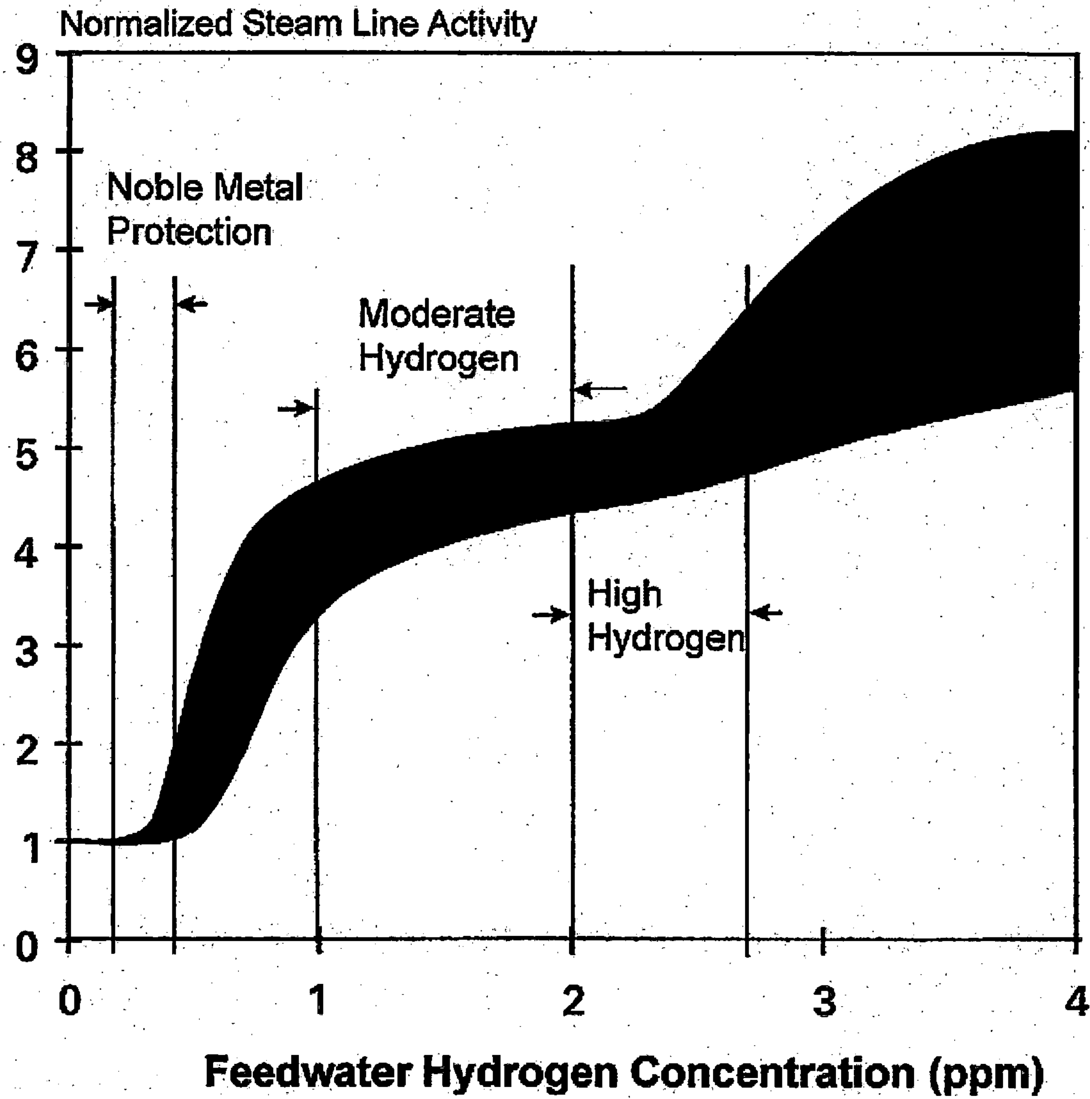

Figure 1-13
Steam Line Activity as A Function of Hydrogen Concentration

The first application of NMCA to a commercial BWR was a cooperative effort of the BWRVIP, EPRI, IES Utilities Inc., (IES) and GE Nuclear Energy (1-20). A monitoring package was supplied to measure the performance of the application, to study the durability of the NMCA treated surfaces and to verify the fuel performance over several cycles. The program package included sampling during the application process, material deposition samples exposed to the in-plant application process, in-situ ECP electrodes pretreated with NMCA, an in-situ crack growth monitor and a fuel bundle containing six fuel rods also pretreated with NMCA.

After DAEC was at full power, a benchmark study was performed to determine the effectiveness of the treated surfaces. In all cases, ECPs obtained from electrodes pretreated with NMCA were below the IGSCC initiation threshold and were achieved at low feedwater hydrogen concentration that did not cause a significant increase in operating dose rates. This result was consistent with laboratory studies that NMCA was effective as HWC-M in mitigating IGSCC. Since ECPs were reduced below the IGSCC threshold, NMCA is considered to be as effective as HWC-M in mitigating IGSCC.

NMCA requires that sufficient catalytic material be present on plant surfaces, and that the hydrogen/oxygen molar ratio be maintained >2. Recent results indicate that at Pt plus Rh loading level of 0.01 to 0.03 μg/cm2 is sufficient to produce an ECP <–230 mV(SHE) on NMCA coated surfaces when the hydrogen to oxygen molar ratio was 2.2, Figure 1-14 (1-21). Laboratory tests indicate that the binary Pt plus Rh chemical treatment synergistically creates a more adherent deposit than either of the elements used singly. Pt and Rh were also chosen because of their benign neutron activation products (1-22).

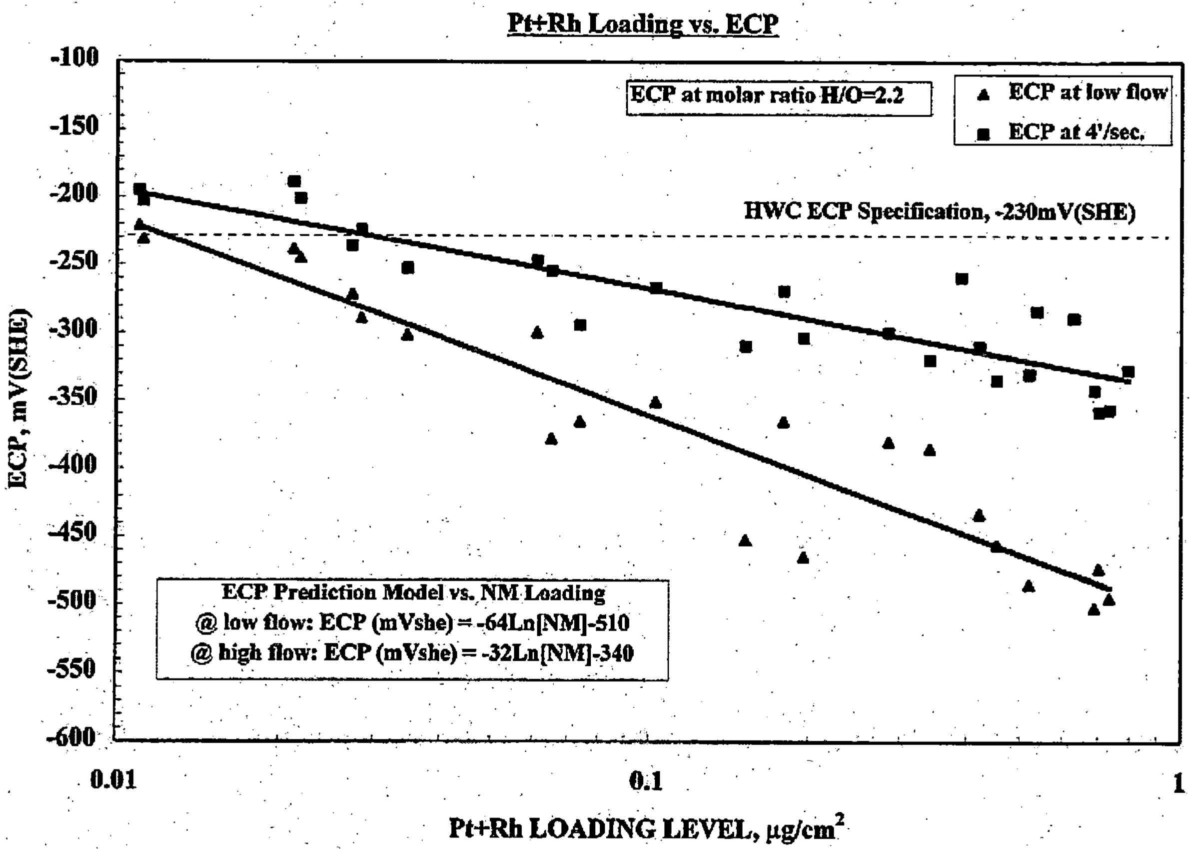

Figure 1-14
ECP as a Function of Pt and Rh Loading Level (1-22)

1.8 Mitigation of Deep Cracks by HWC-M or NMCA

Theoretical and experimental studies have been conducted to determine crack mouth and crack tip pH and potentials in stainless steels in BWR normal water chemistry (NWC) and hydrogen water chemistry (HWC) environments and their role in IGSCC (1-24). These studies clearly show that in an oxidizing BWR environment:

- The potential at the crack tip is low typically ~ -600mV(SHE).
- The potential at the crack mouth is high ~ 0 to +100mV(SHE).
- Because of the potential gradient the pH at the crack tip becomes more acidic and more concentrated in anionic species such as chloride and sulfate which may be present in bulk water.

The IGSCC process in NWC is driven by a combination of the aggressive crack tip environment, applied and residual stresses and a susceptible material.

In the HWC environment:

- The potential at the crack tip is low.
- The potential at the crack mouth is low.
- In the absence of a potential gradient the pH at the crack tip stays near neutral and there is little concentration of anionic species.

In HWC-M or NMCA environments the IGSCC process slows down because the crack tip environment is less aggressive than in an NWC environment.

Studies have also shown that localized crack tip chemistry can exist in cracks when they reach depths of 2 mil (50 microns) or more. Crack growth tests show that deep cracks respond to HWC in the same way as shallower cracks with depths of 2 mil or more. It is the potential difference between the crack tip and crack mouth that determines whether an aggressive environment will be created at the crack tip. HWC-M or NMCA mitigates IGSCC by eliminating or reducing the potential gradient between the crack mouth and crack tip which leads to a less aggressive environment at the crack tip irrespective of crack depth.

1.9 NEI 03-08 Implementation Requirements

This report is provided for information. However, if the report is used to justify inspection relief for piping and internal components at BWRs that have implemented either moderate hydrogen water chemistry or Noble Metal Chemical Application, then the implementation steps described in Section 3.5 and 3.6, Tables 3.7 and 3.8, and Sections 4.6 are "needed" in accordance with the implementation requirements of Nuclear Energy Institute (NEI) 03-08, "Guideline for the Management of Materials Issues".

1.10 Summary of IGSCC Observations and Environmental Mitigation

The issue of IGSCC of austenitic materials has plagued the BWR industry for many years. As remedial measures were applied and research continued, it was discovered that water quality and dissolved oxygen/hydrogen peroxide content were critical factors in causing IGSCC in the BWR environment.

HWC was developed in the 1980s as a remedy to IGSCC in recirculation piping systems and, ultimately, for reactor internals. The beneficial effect of HWC was to decrease the corrosion potential by removing most of the oxygen and other oxidizing species such that the electrochemical driving force for IGSCC was no longer present. However, laboratory studies demonstrated that changing only the corrosion potential was not sufficient to eliminate IGSCC in the presence of HWC. It was also necessary to control impurity levels. Laboratory and in-plant studies have shown that effective environmental controls, consisting of maintaining high water purity and adding sufficient hydrogen to the feedwater to suppress the formation of the oxidizing radiolytic products oxygen and hydrogen peroxide, can minimize IGSCC in the BWR.

NMCA involves the injection of soluble Pt and Rh compounds into the reactor water to deposit those catalytic metal atoms on reactor internal surfaces. The NMCA process protects reactor internals by achieving the similar level of HWC-M protection at a lower feedwater hydrogen concentration with essentially little N-16 penalty. In summary, the benefits of NMCA are as follows:

1. Reduced demand for reactor water hydrogen concentration.
2. Return to NWC operation doses rate, i.e., essentially eliminating the up to 4 to 5x increases in steam turbine radiation fields associated with HWC-M. This also eliminates the administrative controls to deal with increased operating dose.
3. Decrease in personnel exposure during operation.
4. Elimination of increased localized shielding requirements.

However, questions concerning NMCA include impact of ISI on catalyst loading and protection, durability of the deposit, monitoring for the continued presence of the deposit and, of course, implementation cost.

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2
RADIOLYSIS AND ECP MODELS

2.1 Introduction

BWRs use high purity water as the neutron moderator and primary coolant in the production of steam. As a result of water radiolysis (decomposition and recombination of water molecules due to neutron and gamma radiation), liquid-vapor phase equilibrium, and recirculation, the coolant in the BWR recirculation line contains oxidant (oxygen plus approximately half the concentration of hydrogen peroxide) in the concentration range from 150 to 600 ppb. This range of oxidant concentration under normal water chemistry (NWC) operation results in high ECP and increases the susceptibility of reactor vessel internals to IGSCC, when other requisite factors such as threshold tensile stress and sensitization are present.

2.1.1 In-Plant Monitoring

As noted in Section 1, it has been determined that the oxidant concentration and thus ECP can effectively be reduced by the use of hydrogen and that IGSCC can be mitigated. A full-scale implementation test of adding hydrogen in the BWR flow circuit was performed at Dresden-2 in 1982 (2-1 through 2-3). This test demonstrated engineering feasibility and defined process parameters for HWC operation for mitigation of IGSCC in an operating reactor's recirculation system piping. Since the first Dresden-2 test, nearly 20 HWC tests have been performed at various plants. In the majority of these tests hydrogen was added via the feedwater in amounts sufficient to suppress the oxygen in the recirculation system to the low value required to attain protection from IGSCC. In some of the HWC tests the feedwater hydrogen concentration was raised to levels sufficient to indicate mitigation not only for the recirculation piping, but also for some of the internal components.

Experimental data indicate that reducing the level of oxygen to the range of 1 to 10 ppb, which results in a decrease in the ECP to <–230 mV (SHE), can effectively mitigate IGSCC in austenitic stainless steels and nickel-based alloys (2-4) when the water purity is sufficiently high, i.e., conductivity less than 0.3 µS/cm. Results reported in References 2-5 through 2-12 show that with increasing hydrogen in the feedwater, the ECP decreases and as the ECP on Type 304 stainless steel decreases to less than -0.230 V (SHE), cracks from IGSCC do not initiate and propagation rates of existing cracks become extremely low. Thus, ECP serves as a good measure of IGSCC control.

Besides the reactor recirculation system, it is also important to investigate the concentration of hydrogen and oxidizing species in other regions of the primary circuit, where it may be possible to reduce the oxidant concentration to levels sufficiently low for IGSCC mitigation. Three such regions are the in-vessel regions below the fuel support plate (lower plenum), the core bypass region, and the downcomer. In each of these regions, IGSCC has been observed in internals at various locations.

One approach for investigating the concentration of hydrogen and oxidizing species in these regions is via sampling (2-13 through 2-15). This would be difficult and costly. The results are difficult to interpret because of decomposition of hydrogen peroxide in the sampling lines. In addition, it would not provide information for areas outside the sampled regions. Direct ECP measurements would be equally difficult. To date, ECP measurements have been performed with in situ reference electrodes only in the recirculation lines and the bottom head drain line or with in-core probes (modified local power range monitors [LPRMs]).

2.1.2 Model Simulation

Recognizing the difficulties of in-plant monitoring, analytical modeling provides the best alternate approach. Computer simulation of water radiolysis can describe concentrations of hydrogen, oxygen, hydrogen peroxide and other labile hydrogen-oxygen species in the various parts of the BWR primary circuit and in the main steam (2-14 through 2-19). Based on these results, ECP values in all the relevant regions can then be estimated in evaluating SCC mitigation.

Over the years, EPRI and the BWRVIP have been working with GE in developing and improving radiolysis and ECP calculations (2-16, 2-20 through 2-23). Results of research works (2-16, 2-18, 2-19) provide details of the model's parameters, the input data, mass balance calculations, ECP correlations, and the application of computer simulations to a study of 10 BWR plants that, with one exception, had undergone HWC tests or implementation. Independently, GE has performed over twenty plant analyses for HWC operation for IGSCC mitigation. There are sufficient data to benchmark the computer simulation for actual plant applications.

In 1998, GE, AEA Technology (Harwell), and EPRI/BWRVIP signed license agreements to provide the GE/Harwell radiolysis/ECP computer model (2-24, 2-25) to EPRI/BWRVIP members for plant applications. For user friendly features and software quality control, the EPRI CHECWORKS™ platform (2-26) is utilized to provide graphical user interface and database management to launch the radiolysis and ECP analysis (2-27). In the following, details of the BWRVIP/GE/Harwell (BWRVIP) model and its technical basis for plant application are described.

2.2 Model Description

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The following sections are based on evaluations using BWRVIA V1.0, except where indicated. The BWRVIP is continuing to refine the model and to reduce uncertainties in the model predictions, particularly in the lower head region. In response to Open Item 3.2.4, the BWRVIP will submit its review of other radiolysis/ECP models along with the results of its refinements to BWRVIA for NRC review at a later date.

2.2.1 *Radiolysis Model*

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2.2.1.1 Flow Circuit Schematics

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Figure 2-1
Computer Model of BWR Primary System

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Figure 2-2
Radiolysis Model Region and Circuit Identification

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Figure 2-3
Simplified Schematic of Steam Separator

2.2.1.2 Model Numerics

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2.2.2 Dose Rate Calculations

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2.2.3 Model Input Parameters

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2.2.4 ECP Calculations

2.2.4.1 BWRVIA V1.0 ECP Calculations

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2.2.4.2 BWRVIA V2.0 ECP Calculations

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2.2.5 *Model Output Files*

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2.3 Simulation vs. Measurement

2.3.1 *BWRVIA Version 1.0*

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Figure 2-4 combines the comparison of calculated and measured hydrogen concentrations in the condensed steam at various feedwater hydrogen concentrations. The maximum deviation between the two sets of values is only a few percent at zero ppm feedwater hydrogen. Two plants show better agreement with increasing feedwater hydrogen. All three show acceptable agreement between Content Deleted - EPRI Proprietary Information feedwater hydrogen. The predicted minimum in the steam hydrogen occurs at approximately Content Deleted - EPRI Proprietary Information feedwater hydrogen, while experimentally the minimum occurs at Content Deleted - EPRI Proprietary Information. The agreement is also reasonable for the corresponding comparison of oxygen data of Figure 2-5. The prediction of the model for the steam hydrogen and oxygen concentrations is virtually identical for the three plants.

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Figure 2-4
Comparison of Calculated and Measured Steam Hydrogen Concentrations

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Figure 2-5
Comparison of Calculated and Measured Steam Oxygen Concentrations

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Figure 2-6
Comparison of Calculated and Measured Recirculation Hydrogen Concentrations

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Figure 2-7
Comparison of Calculated and Measured Recirculation Oxidant Concentrations

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**Figure 2-8
Comparison of Calculated and Measured ECP Values**

2.3.2 Validity of BWRVIA Version 1.0 Predictions

In Section 3.2 of the final SE the NRC requested a discussion of the significant differences between the G values and rate constants used in BWRVIA and those values used in similar models developed in Taiwan (2-33) and Japan (2-34). The NRC also requested further discussion of the differences between measured and BWRVIA predicted ECPs in the lower vessel head region. This section fulfills the requirement from the NRC Safety evaluation to update BWRVIP-62 with the information (including tables and figures) submitted by the BWRVIP in August 2001. The material has been updated to provide references for work that has been completed since August 2001.

The G values and reaction rate constants and some of the radiolysis schemes in the EPRI model were based on the state of the art in late 1980s. At that time the integrated set of constants gave the best correlation of plant measurements. It was recognized that model inputs have a range of uncertainties that would result in uncertainties in predictions. The approach to address these uncertainties was to compare the model predictions of hydrogen, oxygen and ECP at specific locations to plant measurements of the same parameters at the same locations. These comparisons are discussed in Section 2.3 and summarized in the following paragraphs. The results reported in Section 2.3 were developed based on the 1998 version of the BWRVIP radiolysis/ECP model (BWRVIA Version 1.0). This is a later version of the model compared to the one that was used to prepare BWRVIP-13 in 1995.

It should be noted that while the model calculates oxygen, hydrogen and ECP throughout the plant, most actual in-plant measurements are made of oxygen and hydrogen concentrations in the reactor water. A few plants have also measured hydrogen and oxygen in steam. Reactor water oxygen and hydrogen and steam oxygen are also listed as secondary parameters in Table 3-5.

Figures 2-4 and 2-5 show a comparison of measured and calculated steam hydrogen and steam oxygen data for three plants. Similarly, Figures 2-6 and 2-7 show the calculated and measured hydrogen and oxidant data in the recirculation system for four plants.

Figure 2-10 presents data from Susquehanna-2 comparing chemistry measurements to model predictions (2-33). Again there is good agreement between the measured oxygen in the reactor water and that predicted by the model. Similarly there is close agreement between the measured and predicted hydrogen in the reactor water.

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Figure 2-9
MPM ECP vs. Flow (Reynolds Number), Oxidant and Oxidant Concentration

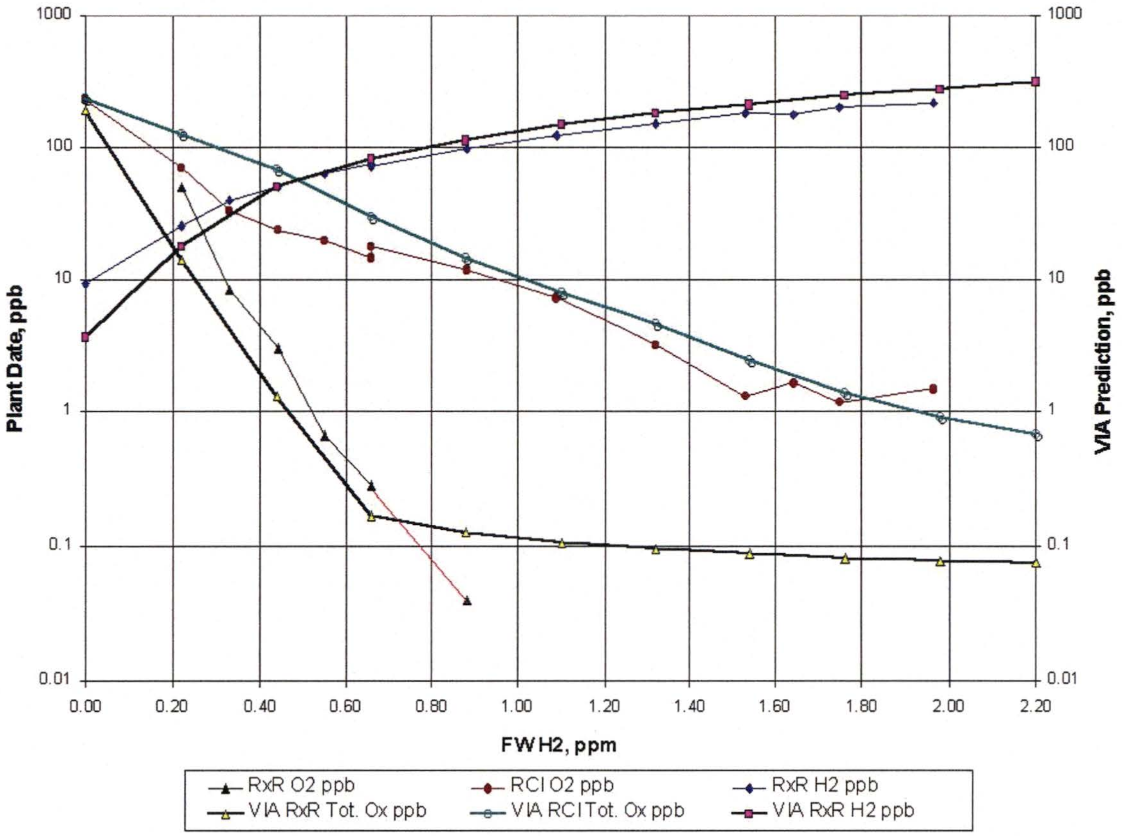

Figure 2-10
SSES-2 HWC Startup Chemistry vs. BWRVIA Predictions (2-33)

RxR – Reactor Recirculation Sample
RCI – Reactor Water Cleanup Inlet Sample
VIA – BWRVIA Radiolysis Model Prediction

The comparisons of model predictions of hydrogen and oxygen versus plant measurements show that the BWRVIA radiolysis ECP model is in good agreement with chemistry measurements for reactor water and steam systems. The comparisons cover a range of BWR types, core power outputs, core radii and power densities as shown in Table 2-1.

Table 2-1
BWR Plants used in BWRVIA Model vs. Chemistry/ECP Comparisons

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Figure 2-11 shows a comparison of ECP measurements and model calculations below the core plate at Susquehanna-1 during Cycle 11 HWC startup (2-33). The model predictions and plant measurements show reasonable agreement. The model predictions of ECP are conservative compared to measurements at this location.

Figure 2-12 presents ECP data from probes located in the lower vessel head region at Susquehanna-2. In this location the BWRVIP model underestimated the hydrogen injection rate required to achieve protection (−230 mV) by approximately 40%. The ECP data and model showed better agreement at hydrogen concentrations equal to or greater than 1.6 ppm. For this plant the ECP model was more accurate in the core plate region than in the lower vessel head region.

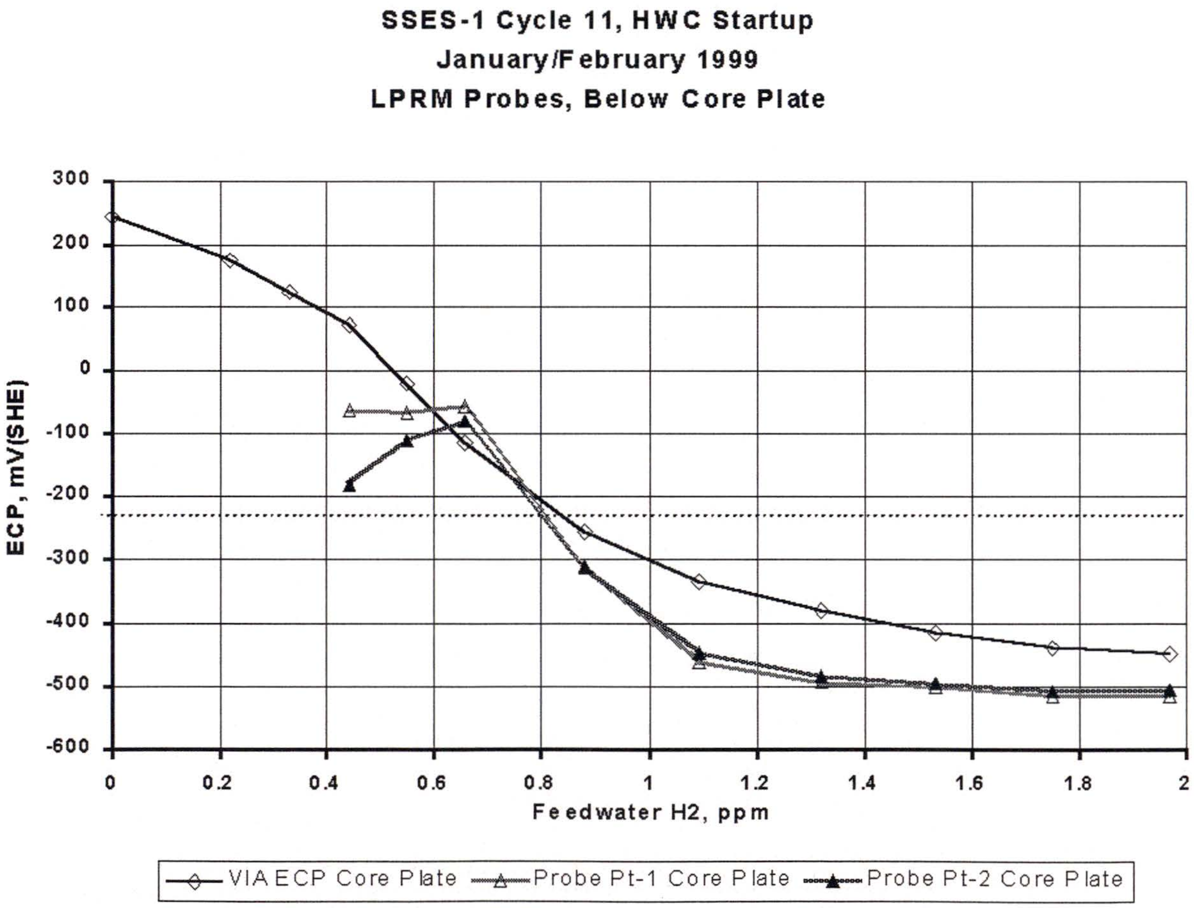

Figure 2-11
Predicted and Measured ECP below the Core Plate, SSES-1

VIA – BWRVIA Radiolysis Model Prediction

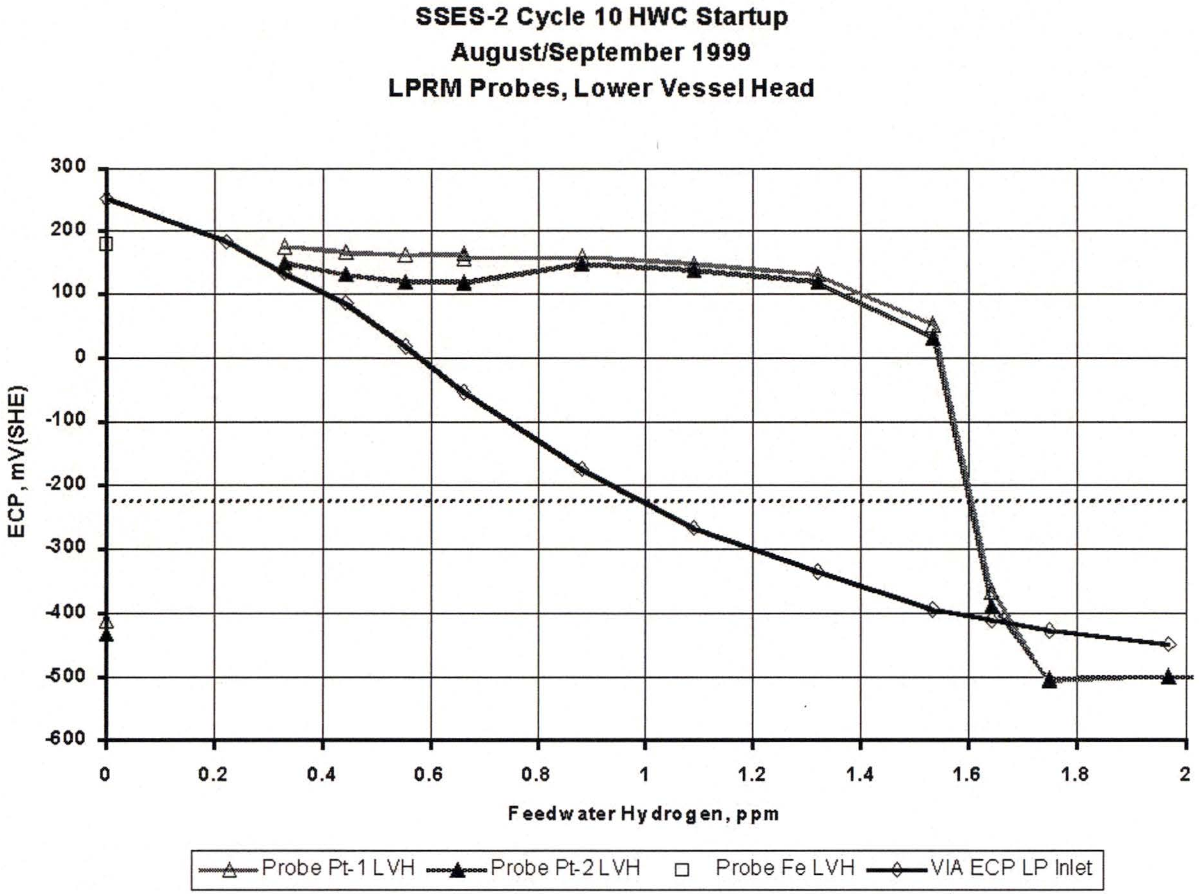

Figure 2-12
Predicted and Measured ECP in the Lower Vessel Head, SSES-2

LVH – Lower Vessel Head
LP – Lower Plenum (same as LVH)
VIA – BWRVIA Radiolysis Model Prediction)

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Therefore, based on the above discussion, the BWRVIP believes that BWRVIA Version 1.0 (which was the model in use in 2001) shows good agreement with plant chemistry data as well as plant ECP data at specific locations. Additional work is planned to reduce the observed ECP uncertainties in the lower plenum region.

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Figure 2-13
Comparison of Calculated and Measured ECP Values

2.3.3 BWRVIA V2.0 Simulation vs. Measurement

Subsequent to the development of Version 1.0 of the model there have been experiments and research conducted to quantify the fundamental chemical-physical constants and reaction schemes. BWRVIP has completed a review of G values and rate constants and has incorporated updated values in BWRVIA Version 2.0 (2-32), which was released in June 2003. Minor revisions were made with Service Release 1 in October 2005 (2-31).

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Figure 2-14 shows the BWRVIA V2.0 predictions for ECP compared to data taken during the Susquehanna-1 ramping test. It shows that the ECP in the lower plenum decreased to −230 mV SHE at a feedwater hydrogen concentration of 1.6 ppm. This value was ~25% higher than that predicted by the BWRVIA model which means that the model was non-conservative. In another case (Garona) the model was conservative in lower plenum as shown in Figure 2-15.

BWRVIP is continuing work to further refine the model and to reduce uncertainties in the model predictions particularly in the lower vessel head region. The planned work will include a review of the G values used in the two NRC references cited below. Currently BWRVIP does not have sufficient information to comment on the radiolysis ECP models discussed in (2-34) and (2-35).

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Figure 2-14
Susquehanna 1 Lower Plenum ECP vs. Feedwater Hydrogen BWRVIA 2.0

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Figure 2-15
Garona Lower Plenum ECP vs. Feedwater Hydrogen BWRVIA 2.0

2.4 Summary

GE Nuclear Energy, AEA Technology (now National Nuclear Laboratory UK) and EPRI have been using and developing radiolysis/ECP computer models for over ten (10) years. Simulations have been performed for 23 BWRs. Where reliable chemistry measurements have been made on the steam and recirculation piping, the model is in excellent agreement with the measurements. In all the simulations performed, the model tends to provide reasonable hydrogen and oxygen results. As with the hydrogen, there are significant plant-to-plant differences in the oxygen.

Assuming that crack initiation is fully mitigated at −230 mV(SHE), calculated results indicate that, in general, mitigation can be achieved with HWC-M at hydrogen levels between Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information depending upon the region and plant. The H_2 required for mitigation is different in the outer core bypass region (the outer core bypass region corresponds to the inner surface of the core shroud), in the lower section of the downcomer, in the recirculation lines, and in the lower plenum. In some other regions of the primary circuit, mitigation can be achieved only with higher concentrations of feedwater hydrogen or cannot be achieved within the range of hydrogen concentrations modeled Content Deleted - EPRI Proprietary Information.

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3

HYDROGEN WATER CHEMISTRY EFFECTIVENESS ASSESSMENT

3.1 Background

As discussed in Section 1, HWC has been shown to be effective in mitigating both IGSCC initiation and IGSCC growth in austenitic stainless steel and nickel-based alloy components exposed to BWR operating conditions. Components for which HWC is effective include reactor recirculation and related piping systems and portions of the reactor internal systems. This section of the report emphasizes the effect of HWC on reactor internal components' performance.

As noted in Section 1, the key parameter that determines the magnitude of IGSCC mitigation is the ECP of the material in the region of interest. However, it is not technically feasible to measure the ECP of all susceptible locations. Therefore, the prudent approach is to measure the ECP under conditions that bound or can be correlated with those at the most difficult component for which protection is required, i.e., the component that requires protection that is exposed to the most aggressive environment. The parameters that need to be considered in demonstrating that ECP is being measured at a specific location, which is not the monitoring location, are temperature, chemistry, extent of chemistry changes, (e.g., peroxide decay).

ECP modeling efforts and in-plant studies provide reasonable assurance that ECP measurements at locations remote from the component of interest provide a useful indication of the degree of IGSCC mitigation. An alternate approach is to monitor secondary parameters and to demonstrate a correlation of these parameters to IGSCC mitigation.

Generally, in-plant measurements of ECP have demonstrated that higher hydrogen injection rates into the feedwater are required to achieve mitigation inside the reactor vessel than are required to achieve mitigation in the recirculation piping. One exception to this trend is Quad Cities Unit 2, where recirculation piping required higher hydrogen injection rates to achieve protection than did specific in-vessel regions (3-1). However, this unusual result was predicted by the radiolysis model for large low power density plants such as Quad Cities Unit 2 (3-2). Also, within the reactor vessel, higher hydrogen levels are required for locations that are higher in the vessel.

3.2 Status of Plant Operating Experience

3.2.1 Present Status of HWC Experience

There has been a significant improvement in the understanding of HWC since the data presented in the BWR Owner's Group Response to NRC on HWC piping inspection relief credit in 1991 (3-3). This increased understanding has been largely obtained from in-plant HWC test programs and through the operational experience gained from the 21 BWRs now operating with HWC. Table 3-1 details the status of plants with HWC implementation (3-4). The thrust of the recent testing and subsequent operation has been to evaluate the hydrogen addition requirements needed to effectively mitigate the lower plenum reactor pressure vessel region, in addition to the recirculation system piping. The new data continues to confirm much of the previous experience. These programs have led to an increase in data from in-situ ECP measurements including those obtained from the recirculation piping. Table 3-2 displays the measured required feedwater hydrogen levels needed to achieve −230 mV(SHE) as a function of component location from nine plants that have performed extensive HWC ramping studies. Some specific ramping data, which are presented in the following paragraphs of this section, support the use of alternate chemistry measurements in lieu of direct ECP measurements (3-4).

Table 3-1
Worldwide BWR HWC Implementation Status as of 1996 (3-4)

Plant Status	U.S. and Mexico	Europe	Asia	Total
Injecting Hydrogen	14	5	2	21
Installing HWC Equipment	12	1	4+	17+
Evaluating/Planning HWC	11	2	many	many

Table 3-2
Feedwater Hydrogen Concentration, in ppm, Required to Reach −230 mV(SHE) in the Indicated Regions of the Reactor Coolant System with Moderate HWC (3-4)

Plant	Recirculation Piping	Lower Plenum	Lower Core	Upper Core
Duane Arnold*	0.3	-	1.2	> 2.2
FitzPatrick	-	-	1.0	2.7
Quad Cities	2.3	-	1.4	2.0
Monticello	-	1.5	-	-
Hatch 1	0.5	1.0	1.5	2.0
Pilgrim	1.2	-	1.0	1.8
International Plant-1	-	-	1.4	1.9
International Plant-2	-	-	> 0.6	-
International Plant-3	0.6	-	-	-

* Prior to NMCA

The global view of the benefits of HWC is well-documented (3-2, 3-5 through 3-8). IGSCC mitigation with HWC is addressed, along with discussion of the variation of HWC effectiveness for the different types of BWRs, (e-g., non-jet pump, low-power density and high-power density plants). These new efforts also validate the different methods to verify IGSCC protection including monitoring approaches. Additionally, the experience gained through the many laboratory and plant testing programs, as well as plant operational efforts, strengthen the conclusions that are presented in this report (3-9 through 3-14).

3.2.2 Review of Current Piping Inspection Experience with Hydrogen Water Chemistry

IGSCC benefit for those plants operating with some HWC is clearly supported by recent recirculation system piping inspections. Table 3-3 summarizes the HWC injection experience of those plants that have been injecting hydrogen during previous cycles (3-2). With the exception of one plant, there were no new indications or changes from previous inspections. The one new measurable indication at Dresden-2 was limited in depth Content Deleted - EPRI Proprietary Information and length that is consistent with the operating conditions including time operating with NWC. As illustrated in Table 3-4, the estimated HWC availability differed for each of the plants over the recent cycles. Duane Arnold has operated during cycle 11 through 14 on HWC maintaining at least Content Deleted - EPRI Proprietary Information availability at ECPs below the HWC protection potential. During cycle 15 the plant had applied NMCA and also maintained a HWC availability greater than Content Deleted - EPRI Proprietary Information. No recirculation line cracking has been observed at Duane Arnold for several cycles.

FitzPatrick has been on HWC during operating cycles 10 through 13. As illustrated in Table 3-4, the plant availability on HWC varied from Content Deleted - EPRI Proprietary Information during cycle 10 to almost Content Deleted - EPRI Proprietary Information during cycle 13. It was noted that the protection potential of the recirculation piping was never achieved due to an in-situ ECP measurement of Content Deleted - EPRI Proprietary Information feedwater hydrogen during operating Cycle 11. Later cycles operated up to Content Deleted - EPRI Proprietary Information feedwater hydrogen but there was no confirming ECP measurement. Nevertheless, no IGSCC has been detected in the recirculation system piping at FitzPatrick during these operating cycles.

Table 3-3
Hydrogen Water Chemistry BWRs Recirculation System Piping Inspection (3-3, 3-15)

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Table 3-4
Hydrogen Water Chemistry Performance History for Duane Arnold, FitzPatrick and Hatch (3-3, 3-15)

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Hatch Unit 1 has been on HWC since September of 1987 (cycle11). A stress corrosion monitoring (SCM) test was performed in November of 1994. The test was conducted to help determine the optimum hydrogen flow rate for mitigation of IGSCC in the reactor lower plenum. As a result of this test, Content Deleted - EPRI Proprietary Information standard cubic feet per minute (SCFM) was selected for optimum crack mitigation for the lower components of the reactor and the recirculation piping. The bottom head drain ECP monitoring during the SCM test indicated Content Deleted - EPRI Proprietary Information (SHE) (routine measurements are in the Content Deleted - EPRI Proprietary Information range) at injection rates greater than Content Deleted - EPRI Proprietary Information SCFM. Fuel Cycles 16, 17, and 18 were characterized by greater than Content Deleted - EPRI Proprietary Information HWC availability, Table 3-4. Results of ultrasonic examinations of the recirculation piping in Hatch Unit 1 for 1R14, 1R15, 1R16, and 1R17 indicated no propagation of cracking into the weld overlays, Table 3-3.

In summary, during the past decade, several plants have operated with HWC during multiple operating cycles. One plant, Duane Arnold, has met Content Deleted - EPRI Proprietary Information HWC availability at ECP values below the protection potential. Several others have operated under less than optimum HWC conditions. However, with the exception of one modest indication at Dresden 2, no IGSCC initiation has been observed. It is noteworthy that for many of these cycles, the availability of HWC has been less than Content Deleted - EPRI Proprietary Information. Therefore, the lack of inspection findings demonstrates the effectiveness of each plant's HWC program in mitigation of IGSCC in the recirculation piping system.

3.3 Approach

This section summarizes the methods that are available to demonstrate that HWC is being effectively implemented. In principle, HWC mitigates IGSCC when ECP is reduced to protective levels. Therefore, the approach is to demonstrate that protective ECPs are being achieved in the regions of the RPV where protection is desired. This will be accomplished by monitoring parameters, referred to as "Primary Parameters," that are fundamentally related to IGSCC mitigation.

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Correlation will be developed between protective chemistry conditions and other plant parameters that respond to hydrogen injection. These will be referred to as "Secondary Parameters" as described in Section 3.4. In general, they are parameters, normally continuously monitored, that verify HWC protection is being maintained.

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Section 3.5 provides details of how effective hydrogen injection programs will be implemented at these plants consistent with BWRVIP-62.

3.4 Secondary Parameters

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3.4.1 Moderate HWC Plants

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3.4.1.1 Hydrogen and Oxygen

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3.4.1.2 Nitrogen-16 Isotope and Main Steam Line Radiation

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The relation of the upper core, lower core and recirculation line ECP to feedwater hydrogen concentration for several BWRs is shown in Figures 3-1 through 3-3 (3-1). The ECP/MSLR level relationships are presented in Figures 3-4 through 3-7. In these cases, the data indicates that the lower core and recirculation piping are protected for all evaluated BWRs when the normalized MSLR level exceeded approximately Content Deleted - EPRI Proprietary Information However, the upper core region did not reach the crack initiation protection ECP at a much higher MSLR level although significant reductions in ECP and, thus, predicted crack growth rate could occur at a normalized MSLR value of Content Deleted - EPRI Proprietary Information.

More specifically, a program has been performed at the BWR-3 Santa Maria de Garoña to determine the lower plenum ECP as a function of hydrogen injection rate (3-16).

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Figure 3-1
ECP Correlated with Feedwater Hydrogen Concentration Using In-Core Measurements Obtained Near the Top of the Core of Six Different BWRs (3-1)

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Figure 3-2
ECP Correlated with Feedwater Hydrogen Concentration Using In-Core Measurements Obtained Near the Bottom of the Core of Six Different BWRs (3-1)

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Figure 3-3
ECP Correlated with Feedwater Hydrogen Concentration Using Measurements Obtained In Recirculation Piping for Four Different BWRs (3-1)

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Figure 3-4
ECP Correlated with Normalized MSLR Using In-Core Measurements Obtained Near the Top of the Core for Six Different BWRs (3-1)

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Figure 3-5
ECP Correlated with Normalized MSLR Using In-Core Measurements Obtained Near the Bottom of the Core for Six Different BWRs (3-1)

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Figure 3-6
ECP Correlated with Normalized MSLR Using In-Core Measurements Obtained At the Bottom Drain Line for Two Different BWRs (3-1)

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Figure 3-7
ECP Correlated with Normalized MSLR Using Measurements Obtained In Recirculation Piping for Four Different BWRs (3-1)

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Figure 3-8
Santa Maria de Garoña ECP and Normalized MSLR Correlation for Six Different LPRM Locations (3-17)

3.4.1.3 Main Steam Oxygen

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Figure 3-9
ECP Correlated with Main Steam Oxygen Using In-Core Measurements Obtained Near the Top of the Core for Five Different BWRs (3-1)

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Figure 3-10
ECP Correlated with Main Steam Oxygen Using In-Core Measurements Obtained Near the Bottom of the Core for Five Different BWRs (3-1)

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Figure 3-11
ECP Correlated with Main Steam Oxygen Using In-Core Measurements Obtained In Recirculation Piping for Three Different BWRs (3-1)

Based on the success of correlating lower core region ECP to the MSLR value or the MS oxygen concentration, such correlations can be used to establish the feedwater hydrogen concentration necessary to obtain IGSCC protection in this region. Obtaining ECP measurements would be advisable to justify direct application of these correlations. This is particularly the case for plants differing from plants in design or operating approaches. For example, direct application of the correlation approach to plants operating with significant reactor water copper levels would not be advisable. However, where a significant level of plant similarity exists, i.e., sister plants, the correlation approach should provide a reasonable basis for establishing feedwater hydrogen concentrations.

3.4.1.4 Secondary Parameters for HWC-M BWRs

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Table 3-5
Example of Primary and Secondary Parameters for BWR HWC Categories

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3.4.2 NMCA Plants

As discussed in Section 1.7, since NMCA provides a catalytic surface, the recombination of hydrogen and oxidizing species occurs at the surface. Therefore, less hydrogen is required to achieve the same decrease in ECP with NMCA.

Effectiveness of NMCA is dependent on the hydrogen to oxygen molar ratios present in the regions of concern. Ratios equal to or greater than two are required to demonstrate effectiveness. In fact, due to the higher diffusivity of hydrogen than oxygen in water, the hydrogen to oxygen molar ratio must exceed only 1.83 in BWR water to obtain recombination on the metal surface (3-19). To provide additional IGSCC margin and conservatism, it is recommended that higher measured hydrogen to oxygen molar ratios be utilized such as a hydrogen to oxygen molar ratio of three, (e.g., hydrogen/oxygen = 3). In other words, while a hydrogen to oxygen molar ratio of two is certainly sufficient for NMCA, a measured hydrogen to oxygen molar ratio of three would be recommended for added mitigation margin.

3.4.2.1 Hydrogen, Oxygen and Their Molar Ratio

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3.4.2.2 Steam Line Radiation Effects

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3.4.2.3 Secondary Parameters for NMCA BWRs

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3.4.3 Frequency of Monitoring Secondary Parameters

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3.5 Implementation of BWRVIP-62 for HWC-M Plants

3.5.1 Category 1 HWC-M Plants (ECP Measurements)

3.5.1.1 Primary Parameter

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3.5.1.2 Secondary Parameters

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The secondary parameters shall be validated once every ten years. However, if a plant implements a major power uprate (e.g. > 5%) then a revalidation of secondary parameter is necessary.

3.5.1.3 Application of BWRVIA Radiolysis/ECP Model

It is not practical to use ECP probes at all locations in the vessel or piping. The plant shall use the BWRVIA model (at beginning and end of cycle) to ensure that effective HWC is being maintained in the non-monitored locations (i.e. locations without ECP probes) within the vessel and piping. The end of the fuel cycle should represent the most conservative case, i.e., there should be an elevation in ECP (or an increase in the hydrogen injection rate needed to maintain ECP <−230 mV(SHE)) at the end of the cycle.

In general, the chemistry predictions of the BWRVIA model are in good agreement with plant measurements. The BWRVIA model shall be used to calculate the total oxidant ($O_2 + 0.47\ H_2O_2$) concentration at the location of interest as a function of feedwater hydrogen concentration. (In technical literature the total oxidant is rounded off to $O_2 + 0.5\ H_2O_2$). Figure 3-15 shows the predicted oxidant concentration in the outer by pass region vs. the feedwater hydrogen at beginning and end of cycle for Susquehanna 1. The oxidant concentration decreases below Content Deleted - EPRI Proprietary Information ppb at a feedwater hydrogen of Content Deleted - EPRI Proprietary Information. Figure 3-16 shows a similar plot for the lower vessel head region. It shows that a hydrogen concentration in excess of Content Deleted - EPRI Proprietary Information is required to suppress total oxidant to Content Deleted - EPRI Proprietary Information ppb or less. The BWRVIA model will be used to calculate total oxidant concentrations at various components along the flow path as a function of feedwater hydrogen. As discussed in Section 1.6.2, IGSCC at these locations will be mitigated when the feedwater hydrogen is sufficient to decrease the total oxidant to Content Deleted - EPRI Proprietary Information ppb or less.

As discussed in Section 1.4, a study of the effect of flow rate on ECP and IGSCC conducted by BWRVIP (1-12) showed that high flow increased the ECP but did not have an adverse effect on crack initiation or propagation. In some cases crack growth rate decreased significantly when the flow rate was increased from Content Deleted - EPRI Proprietary Information The study shows that it is inappropriate to use a high flow ECP to estimate crack growth. It is more reasonable to use the low flow ECP because the crack growth rate under low flow conditions is either similar to or higher than that under high flow conditions.

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Because of uncertainty in ECP predictions it is recommended that feedwater hydrogen should be high enough to satisfy both total oxidant and ECP criteria in non-monitored locations:

1. Total oxidant from BWRVIA model shall be equal to or less than Content Deleted - EPRI Proprietary Information ppb and
2. Low flow ECP from the BWRVIA model shall be less than Content Deleted - EPRI Proprietary Information SHE

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Figure 3-12
Proposed Alloy 182 Crack Growth Rate Disposition Curve for NWC at or Below Action Level 1 (3-21)

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Figure 3-13
Proposed Alloy 182 Crack Growth Rate Disposition Curve for High Purity NWC (<0.15 µS/cm) (3-21)

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Figure 3-14
Proposed Alloy 182 Crack Growth Rate Disposition Curve for HWC (3-21)

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Figure 3-15
Predicted Total Oxidant in Outer Bypass for Susquehanna 1

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Figure 3-16
Predicted Total Oxidant in the Lower Vessel Head Region for Susquehanna 1

3.5.2 Category 2 HWC-M (No ECP Probes)

The plants in Category 2 may operate for one cycle under the following guidelines. In order to continue to receive inspection relief, these plants will need to install ECP probes at the next refuel outage and implement the requirements for Category 1 HWC-M plants.

These plants shall use the BWRVIA model to estimate the total oxidant and ECP at various locations as discussed in the previous section. If ECP vs. feedwater hydrogen measurements from a sister plant (Section 3.7) are available then these shall be used to verify the model predictions. Similarly ECP vs. secondary parameter data from sister plants shall also be used if available. The criteria for mitigation will be the same as those for Category 1 plants:

1. Total oxidant from BWRVIA model shall be equal to or less than Content Deleted - EPRI Proprietary Information ppb and
2. Low flow ECP from the BWRVIA model shall be less than − Content Deleted - EPRI Proprietary Information mV SHE

BWRs in this category shall provide additional margin by increasing the hydrogen injection rate because of lack of ECP data directly from the plant.

3.5.3 Summary

Table 3-7 summarizes the implementation steps discussed above for Category 1 and 2 HWC-M plants. BWRVIP believes that the strategies outlined in Table 3-7 are acceptable and will ensure effective HWC-M implementation in BWRs. BWRVIP will continue to monitor and evaluate core shroud inspection data from BWRs that have implemented HWC-M in order to confirm the effectiveness of mitigation in the field.

Table 3-6
Alloy 182 Crack Growth Rate Disposition Equations (3-20)

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Table 3-7
Implementation Steps for Category 1 and 2 (HWC-M) Plants

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3.6 Implementation of BWRVIP-62 for NMCA Plants

3.6.1 Category 3a NMCA Plants (ECP Measurements)

3.6.1.1 Primary Parameters

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Figure 3-17
ECP vs. Feedwater Hydrogen Response of NMCA Treated BWRs

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Figure 3-18
Hydrogen to Oxygen Molar Ratio Calculated by BWRVIA Radiolysis ECP Model for Duane Arnold

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Figure 3-19
Hydrogen to Oxygen Molar Ratio Calculated by BWRVIA Radiolysis ECP Model for Hatch 1

Appendix A provides a physical explanation for the BWRVIA model prediction that the H_2/O_2 molar ratio becomes equal to 2 everywhere in the regions downstream of the feedwater spargers to the boiling regions of the core at a single hydrogen feed rate or FW H_2 concentration.

For an effective NMCA program the noble metal loading should be maintained above 0.1 $\mu g/cm^2$. The loading shall be monitored by periodic removal of durability monitors or by removal and analysis of deposits from artifacts within the vessel.

3.6.1.2 Secondary Parameters

During the hydrogen ramping test the plant shall correlate the ECP with a minimum of two secondary parameters listed in Table 3-5. These secondary parameters shall be used to ensure continued effective NMCA if the ECP probes fail during the cycle.

3.6.1.3 Application of BWRVIA Radiolysis ECP Model

It is not possible to locate ECP probes in all locations of interest in the vessel. The BWRVIA model shall be used to predict the molar ratio at various locations within the vessel and piping as a function of feedwater hydrogen as shown in Figures 3-18 and 3-19. The model prediction of feedwater hydrogen required for a molar ratio of two shall be compared and verified at the location of ECP measurement. A predicted molar ratio of two or more in the non-monitored locations will ensure effective NMCA and IGSCC mitigation.

3.6.2 Category 3b NMCA Plants (No ECP Measurements)

The plants in Category 3b may operate for one cycle under the following guidelines. In order to continue to receive inspection relief, these plants will need to install ECP probes at the next refuel outage and implement the requirements for Category 3a NMCA plants.

3.6.2.1 Primary Parameters

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Appendix A provides a physical explanation for the BWRVIA model prediction that the H_2/O_2 molar ratio becomes equal to 2 everywhere in the regions downstream of the feedwater spargers to the boiling regions of the core at a single hydrogen feed rate or FW H_2 concentration.

For an effective NMCA program the noble metal loading should be maintained above 0.1 $\mu g/cm^2$. The loading shall be monitored by periodic removal of durability monitors or by removal and analysis of deposits from artifacts within the vessel.

3.6.2.2 Secondary Parameters

During the hydrogen ramping test the plant shall correlate the measured molar ratio with a minimum of two secondary parameters listed in Table 3-5. These secondary parameters will be used to ensure effective NMCA if molar ratio measurements are not available.

3.6.2.3 Application of BWRVIA Radiolysis ECP Model

It is not possible to measure the molar ratio at all locations of interest in the vessel or piping. The BWRVIA model shall be used to predict the molar ratio at various locations within the vessel and piping as shown in Figures 3-18 and 3-19. The model prediction of feedwater hydrogen required for a molar ratio of two shall be compared and verified at the location of molar ratio measurement. A predicted molar ratio of two or more in the non-monitored locations will ensure effective NMCA and IGSCC mitigation.

3.6.3 Summary

Table 3-8 summarizes the steps for Category 3a and 3b NMCA plants. BWRVIP believes that the strategies outlined in Table 3-8 are acceptable and will ensure effective NMCA implementation in BWRs. BWRVIP will continue to monitor and evaluate core shroud inspection data from BWRs that have implemented NMCA in order to confirm the effectiveness of mitigation in the field.

Table 3-8
Implementation Steps for Category 3a and 3b (NMCA) Plants

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3.7 Sister Plants

Evaluations by GE, EPRI, and others have established that the plants of nearly identical design and operation will respond to hydrogen injection in a similar manner. These design similarities permit the use of data from such "sister plants" to be used to provide a greater understanding of the effectiveness of HWC-M. The electrochemical definition of a sister plant is straightforward. **Any pair of BWRs (or even a group of BWRs) that are demonstrated to be radiolytically equivalent by a validated and benchmarked radiolysis model are considered to be "sister plants."**

For example, a particular plant may not have direct ECP measurements available to demonstrate the effectiveness of HWC-M in the lower plenum. The performance of a sister plant under HWC-M could be used to provide some evidence of mitigation for its sister. To demonstrate similarity, it is important to compare all parameters that can affect response to hydrogen injection. The objective is to demonstrate comparable response to HWC-M injection as ultimately determined by the amount of hydrogen required to achieve the IGSCC protection corrosion potential of −230 mV(SHE) or some other target ECP for partial protection on surfaces in the region of interest. Parameters that typically would need to be evaluated by the radiolysis model to demonstrate such similarities include (3-8):

1. Plant characteristics

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Plants have often been compared or grouped based upon these factors. Because of differences in other factors such as those that follow, two plants that are identical with regard to geometric and design considerations may respond differently to injection of a specific level of hydrogen.

2. System operation

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3. Water chemistry

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3.8 BWRVIP Crack Growth Modeling for Stainless Steel

3.8.1 Neutron Fluence <5 x 10^{20} n/cm^2

BWRVIP has developed a statistically based correlation of crack growth rate and key mechanical and environmental parameters. The empirical model is designed to predict the crack propagation rate of stainless steels in the BWR environment. The methodology is documented in BWRVIP-14-A (3-19), which has been reviewed and approved by the NRC. The model equation has the following form:

$$1n \text{ of crack growth rate (mm/s)} = a\ 1n\,K - b/C^{C} + d\,ECP + e/T - f$$

Where:

a, b, c, d, e, f = empirically fit constants

K = stress intensity, $MPa\sqrt{m}$

C = conductivity at 25 °C, µS/cm

ECP = electrochemical corrosion potential, mV(SHE)

T = absolute temperature, °K

The best fit model for the Type 304 stainless steel data is:

$$1n\,(da/dt) = 2.181\ 1n(K) - 0.787C^{-0.586} + 0.00362ECP + 6730/T - 35.567$$

The model is a multivariable least squares fit to documented fracture mechanics specimen crack growth rate data available to BWRVIP in 1995. The 95th percentile residuals about the model, which is equal to the crack propagation rate from the best fit model multiplied by 10.3, has been recommended as a conservative representation of the data. The calibration data set included only sensitized, unirradiated, non-cold worked Type 304 stainless steel test results that were characterized by measured values of corrosion potential, conductivity, stress intensity and temperature. The 95th percentile model is conservative for non-sensitized material, other stainless steels including Types 347, 316L and 316NG. It has been accepted by the NRC for application to stainless steels irradiated to a fluence of $< 5 \times 10^{20}$ n/cm^2. Most of the earlier data used in NUREG/CR-0313 Rev. 2 (3-2), for which measured ECP and conductivity are not available, are also bounded by the 95th percentile model under credible assumptions of ECP and conductivity. Figure 1-10 presented in Section 1 shows the predicted crack growth rate versus ECP for the BWRVIP best fit and 95th percentile models for $K = 26.6$ MPa$\sqrt{m}$, $T = 270°C$ and 0.10 µS/cm conductivity, with relevant data. The correlation clearly shows that the predicted crack growth rate decreases as the ECP decreases.

It should be noted that other validated crack growth models such as GE PLEDGE model can be used. The PLEDGE crack growth model uses crack propagation algorithms based on a "first principles" model of crack advance known as the film rupture/slip oxidation model (3-20). PLEDGE calculated crack growth rates are significantly lower than those calculated using the BWRVIP correlation at HWC conditions.

3.8.2 Neutron Fluence $\geq 5 \times 10^{20}$ n/cm^2 and $\leq 3 \times 10^{21}$ n/cm^2

As plants age, certain locations in the mid-plane of the core shroud experience fluence levels exceeding 5×10^{20} n/cm^2. With increasing fluence, the materials become susceptible to irradiation assisted stress corrosion cracking (IASCC). BWRVIP has developed methodologies to evaluate crack growth in internal components of stainless steel applicable to irradiated BWR stainless steel internal components for fluence levels from 5×10^{20} n/cm^2 to 3×10^{21} n/cm^2 that have been approved by the NRC (3-23). K-dependent crack growth curves have been developed that provide a reasonable bound to laboratory data under NWC and HWC conditions. It should be noted that the HWC curve is a factor of three lower than the NWC curve.

The crack growth rates specified in BWRVIP-99-A (3-23) shall be used for evaluating welds that are exposed to neutron fluences above 5×10^{20} n/cm^2, and fluences equal to or less than 3×10^{21} n/cm^2.

3.9 BWRVIP Crack Growth Modeling for Nickel-base Alloys

In response to the IGSCC or, more accurately, interdendritic stress corrosion cracking (IDSCC) in the case of nickel-base weld alloys in the nozzle-to-safe end locations and access hole covers, the BWRVIP has developed crack growth rate disposition curves applicable to components of Alloy 82, 182, and 600 types of nickel base austenitic materials. The curves are based on Alloy 182 (nickel-based weld metal) field and laboratory crack growth data. The crack growth behavior of Alloy 82 and Alloy 600 in the BWR environment is expected to be far better than that of Alloy 182 as demonstrated by field experience. Hence, the crack growth evaluation methodology is conservative in application to Alloys 82 and 600. The disposition curves and supporting analyses are contained in BWRVIP-59-A (3-21), which has been reviewed and approved by the NRC. Disposition curves have been developed for three basic BWR environments: (1) NWC at or below the EPRI Action Level 1 conditions, (2) NWC with conductivity restricted to 0.15 µS/cm or lower and (3) HWC that meets EPRI guidelines. Table 3-6 summarizes these equations. **The NRC has not approved the use of the high purity NWC curve.**

All the Alloy 182 disposition curves are characterized by two parts: a K-dependent curve for stress intensity levels up to Content Deleted - EPRI Proprietary Information and a crack growth rate independent of stress intensity above Content Deleted - EPRI Proprietary Information, Figures 3-12 through 3-14. As was the case for stainless steel, this model clearly shows that the predicted crack growth rate decreases as the ECP decreases. The HWC crack growth rate curve is factor of ten or greater below the NWC Action Level 1 curve, depending on the stress intensity.

3.10 References

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4

TECHNICAL BASIS FOR PROPOSED INSPECTION RELIEF

The NRC and the BWRVIP have provided inspection recommendations for in-service inspections (ISI) of austenitic stainless steel and nickel base alloys used as structural components in the BWR. The NRC requirements for piping systems are provided in NUREG-0313, Rev. 2 and its implementing document Generic Letter 88-01 (4-1). The inspection recommendations for in vessel components are provided in the BWRVIP Inspection and Evaluation (I&E) Guidelines as summarized in Table 4-1 (4-2 through 4-12).

Table 4-1
Summary of Inspection References for BWR Internals (4-2 through 4-12)

Component	BWRVIP Report	EPRI Report	Date
Core Shroud	BWRVIP-76-A	1019057	December 2009
Core Spray	BWRVIP-18-A	1011469	February 2005
Core Plate	BWRVIP-25	TR-107284	December 1996
Top Guide	BWRVIP-26-A	1009946	November 2004
Standby Liquid Control System/Core Plant ΔP	BWRVIP-27-A	1007279	July 2003
Shroud Support	BWRVIP-38	TR-108823	September 1997
Jet Pump Assembly	BWRVIP-41 Rev. 2	1019570	September 2009
LPCI Coupling	BWRVIP-42-A	1011470	February 2005
Lower Plenum	BWRVIP-47-A	1009947	June 2004
Vessel ID Attachment Weld	BWRVIP-48-A	1009948	June 2004

4.1 Piping System In-Service Inspection Requirements

Due to HWC's documented mitigating effects on IGSCC, the BWROG has proposed that credit be given for HWC availability at or above 80% for BWR piping (4-13). The basis for this request was linked to the dramatic improvement in water chemistry accomplished by the BWR industry as reflected by improving fleet coolant conductivity values. These improvements have had a pronounced impact in reducing IGSCC crack growth rates. Evaluations of the predicted impact of these conductivity improvements have established that a large PLEDGE calculated FOI has occurred since the NWC high conductivity typical of plant operation at the time of Generic Letter 88-01. These improvements based on the PLEDGE crack growth model establish that 80% HWC availability can justify FOIs in crack propagation rates that significantly exceed those required for IS1 relief.

Such a reduction is consistent with the requested ISI guidelines of a factor of two reduction in IS1 frequency for all categories of piping and it is also consistent with the water chemistry improvements that apply to BWRs operating under HWC or NWC (4-14).

4.2 BWRVIP Crack Growth Modeling Factors of Improvement for Stainless Steel

The BWRVIP model discussed in Section 3.8.1 and illustrated in Figure 1-10 of Section 1 clearly indicates decreasing crack growth rate with decreasing ECP and supports the implementation of HWC to mitigate IGSCC. The crack growth rates generated from this model can then be utilized to calculate factors of improvements (FOIs) based on HWC availability.

Table 4-2 contains BWRVIP model FOIs over a range of ECP values at 0.3 μS/cm conductivity. This value of conductivity is within Action Level 1 of the EPRI Water Chemistry Guidelines. (Since the model is characterized by a series of parallel lines as a function of conductivity, the identical FOI values would be obtained at other conductivities although the calculated crack growth rates would be different.) The stress intensity for the crack growth calculations was 27.5 $MPa\sqrt{m}$ (25 $ksi\sqrt{in}$). It is important to note that this FOI evaluation, which is based on the model in BWRVIP-14, is limited to locations with fluences $< 5 \times 10^{20}$ n/cm^2. Figure 4-1 presents the data of Table 4-2 plus additional FOI results for other corrosion potentials.

Table 4-2
BWRVIP Crack Growth Modeling Factors of Improvement for Stainless Steel as A Function of HWC Availability for an ECP (BWRVIP-14)

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The results of this analysis suggest that a FOI of Content Deleted - EPRI Proprietary Information is readily obtainable for stainless steel components with neutron fluence $< 5 \times 10^{20}$ n/cm^2 over a relatively wide range of HWC availability and ECPs. For example, from Figure 4-1, a HWC availability of only Content Deleted - EPRI Proprietary Information and a reduction in material ECP to only Content Deleted - EPRI Proprietary Information, a FOI of TS in crack growth rate retardation could be obtained. Similarly, a Content Deleted - EPRI Proprietary Information availability and a reduction in material ECP to Content Deleted - EPRI Proprietary Information mV(SHE) would provide the same IGSCC benefit. Other validated crack growth models such as PLEDGE may be used for generating similar FOI tables.

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Figure 4-1
Stainless Steel IGSCC Crack Growth Rate Factors of Improvement (FOI) vs. HWC Availability as A Function of ECP (3-19) [0.3 µS/cm, 27.5 MPa√m, 288°C]

As discussed in Section 3.8.2, the NRC has reviewed and approved the methodology in BWRVIP-99-A (3-23) for evaluating crack growth rate for stainless steel internal components subject to IASCC. The crack growth rates specified in BWRVIP-99-A shall be used for evaluating welds that are exposed to neutron fluences above 5 x 10^{20} n/cm^2, and fluences equal to or less than 3 x 10^{21} n/cm^2. The HWC crack growth rate curve is a factor of three below the NWC curve. Consequently, a FOI of Content Deleted - EPRI Proprietary Information is readily obtainable for stainless steel components subject to IASCC, over the specified range of neutron fluence. For example, a FOI of Content Deleted - EPRI Proprietary Information in crack growth rate retardation could be obtained with a HWC availability of only Content Deleted - EPRI Proprietary Information.

4.3 BWRVIP Crack Growth Disposition Curve Factors of Improvement for Alloy 182

The BWRVIP disposition curves discussed in Section 3.8 also indicate decreasing crack growth rate with the implementation of HWC. As was the case for stainless steels, the crack growth rates generated from this model can then be utilized to calculate FOIs based on HWC availability. Table 4-3 contains BWRVIP disposition curve FOIs as a function of HWC availability for Alloy 182. As discussed in Section 3.9, the Alloy 182 curve is conservative for Alloys 82 and 600. Since the stress intensity for the crack growth calculations was 27.5 MPa√m (25 ksi√in), then the FOI of HWC over NWC was Content Deleted - EPRI Proprietary Information. Although, as was the case for stainless steels, this FOI evaluation is limited to fluences $<5 \times 10^{20}$ n/cm^2, since BWR nickel-base alloys are not exposed to high fluences, the fluence limit is not a concern. The model has not been validated above this fluence level. Figure 4-2 graphically presents the data of Table 4-3.

Table 4-3
BWRVIP Disposition Curve Factors of Improvement for Alloy 182 as a Function of HWC Availability at an ECP of −230 mV(SHE)

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The results of this analysis suggest that a FOI of Content Deleted - EPRI Proprietary Information is readily obtainable over a relatively wide range of HWC availability. For example, from Figure 4-2, any HWC-M or NMCA implementation where the component ECP <−230 mV(SHE) and on-line availability is Content Deleted - EPRI Proprietary Information _results in a FOI of Content Deleted - EPRI Proprietary Information in crack growth rate retardation.

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Figure 4-2
Plot of Alloy 182 Crack Growth Rate Factors of Improvement (FOI) Based on HWC Availability at an ECP of −230 mV(SHE)

4.4 Vessel Internals IGSCC Mitigation

Based on radiolysis and ECP modeling studies, the extent of IGSCC mitigation can be established for reactor internal components (4-15). Table 4-4 presents a list of typical BWR internal components, whether they are typically creviced or not, their respective BWR cracking history and the degree of IGSCC protection afforded by HWC-M and NMCA (4-16). Although this table was developed specifically for Duane Arnold and has been updated since its original publication, other BWRs would be characterized by very similar results. The "BWR IGSCC History" column indicates identified cracking incidents that have been identified in the BWR industry. The "Inside" and "Outside" columns provide information concerning components that have surfaces in two regions of the reactor coolant circuit such as the core shroud that is exposed to core bypass water chemistry on the inside and downcomer water chemistry on the outside. The term "probable" indicates that although some IGSCC protection is anticipated, the degree of protection cannot be readily determined or quantified at this time or the protection may be effective as a function of the durability of sufficient catalyst loading.

Table 4-4
Example of the Effect of HWC-M and NMCA on BWR Internals IGSCC Propensities Based on an Updated Analysis of Duane Arnold (4-16)

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Table 4-4
Example of the Effect of HWC-M and NMCA on BWR Internals IGSCC Propensities Based on an Updated Analysis of Duane Arnold (4-16) (Continued)

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Table 4-4
Example of the Effect of HWC-M and NMCA on BWR Internals IGSCC Propensities Based on an Updated Analysis of Duane Arnold (4-16) (Continued)

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Table 4-4
Example of the Effect of HWC-M and NMCA on BWR Internals IGSCC Propensities Based on an Updated Analysis of Duane Arnold (4-16) (Continued)

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Table 4-4
Example of the Effect of HWC-M and NMCA on BWR Internals IGSCC Propensities Based on an Updated Analysis of Duane Arnold (4-16) (Continued)

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4.5 Vessel Internals Inspection Recommendations Based on FOIs

Based on the crack growth modeling results discussed in Sections 4.2 and 4.3 and the example of radiolysis results of Section 4.4, a vessel internals inspection program can be developed based on FOIs for plants that have implemented either HWC-M or NMCA. The FOI calculated for each internal component based on modeling results would be applied to revise the internals inspection interval established in the various BWRVIP I&E documents listed in Table 4.1. BWRVIP will propose revised inspection intervals for vessel internals for plants that have implemented either HWC-M or NMCA at a later date.

4.6 Summary: Effective Implementation of Hydrogen Injection for RVIs

Although the NRC has accepted in principle the use of Factors of Improvement (FOI) to revise inspection intervals, the following requirements have been specified for HWC Availability to obtain inspection relief for reactor vessel internals.

4.6.1 HWC Availability

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4.6.2 HWC-M Effective Implementation

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4.6.3 NMCA Effective Implementation

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4.7 References

4-1 W. S. Hazelton and W. H. Koo, "Technical report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," NUREG-0313, Rev. 2, U.S. NRC, January 1988.

4-2 *BWRVIP-76-A: BWR Vessel and Internals Project, BWR Core Shroud Inspection and Evaluation Guidelines*. EPRI, Palo Alto, CA: December 2009. 1019057.

4-3 Included in the above.

4-4 *BWRVIP-18-A: BWR Vessel and Internals Project, BWR Core Spray Internals Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: February 2005. 1010469.

4-5 *BWR Vessel and Internals Project, BWR Core Plate Inspection and Flaw Evaluation Guidelines (BWRVIP-25)*. EPRI, Palo Alto, CA: December 1996. TR-107284.

4-6 *BWRVIP-26-A: BWR Vessel and Internals Project, BWR Top Guide Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: November 2004. 1009946.

4-7 *BWRVIP-27-A: BWR Vessel and Internals Project, BWR Standby Liquid Control System/Core Plate ΔP Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: July 2003. 1007279.

4-8 *BWR Vessel and Internals Program: BWR Shroud Support Inspection and Flaw Evaluation Guidelines (BWRVIP-38)*. EPRI, Palo Alto, CA: September 1997. TR-108823.

4-9 *BWRVIP-41, Revision 2: BWR Vessel and Internals Project, BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: September 2009. 1019570.

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4-11 *BWRVIP-47-A: BWR Vessel and Internals Project, BWR Lower Plenum Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: November 2004. 1009947.

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4-13 Topical Report NEDC-31951P, "BWR Owner's Group Response to NRC Safety Evaluation of BWROG Topical Report, Implementation of Improved Water Chemistry and Technical Basis for Revised Piping Inspection Schedules – April 1991," April 1998. For participating members of the BWROG Improved Water Chemistry Committee.

4-14 W. Sheron, NRC letter to R. A. Pinelli, BWROG, "Safety Evaluation of Topical Report," NEDE-31951P, dated January 1995.

4-15 *BWR Vessel and Internals Project, Modeling Hydrogen Water Chemistry for BWR Applications – New Results (BWRVIP-13).* EPRI, Palo Alto, CA: December 1995. TR-106068.

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5

CONCLUSIONS

The above discussion and present analysis clearly suggest that based on HWC-M or NMCA implementation, inspection relief can be justified for BWR internals. More specifically:

1. Inspection relief is justified for BWR internals at plants that have effectively implemented HWC-M or NMCA.
2. Supplementary techniques for ensuring the effectiveness of HWC-M or NMCA have been developed. Detailed evaluations based on computer models and benchmark testing have demonstrated the viability of using secondary parameters to confirm IGSCC mitigation.
3. A set of parameters has been developed that can be used in the absence of direct ECP measurements or as a supplement to direct ECP measurements for establishing IGSCC mitigation criteria.
4. The BWRVIP developed radiolysis/ECP computer model is in excellent agreement with reliable chemistry measurements of the steam and recirculation systems.

Empirical crack growth models for stainless steel and nickel-base Alloy 182 weld metal indicate that a FOI of Content Deleted - EPRI Proprietary Information S reduction in crack growth rate is readily achievable with a HWC-M or NMCA availability of Content Deleted - EPRI Proprietary Information.

A

PHYSICAL EXPLANATION OF MOLAR RATIO PREDICTIONS OF BWRVIA MODEL

This section provides a physical explanation for the BWRVIA model prediction that the H_2/O_2 molar ratio becomes equal to 2 everywhere in the regions downstream of the feedwater spargers to the boiling regions of the core at a single hydrogen feed rate or FW H_2 concentration.

The basic chemical reactions for hydrogen and oxygen in the reactor are:

Radiolytic decomposition and recombination:

$$8\,H_2O \leftrightarrow 6\,H_2 + 2\,O_2 + 2\,H_2O_2$$

This reaction goes to an equilibrium depending on the concentrations of H_2, O_2 and H_2O_2. If H_2 is added, the reaction shifts to the left, O_2 and H_2O_2 are consumed, and we say "recombination" occurs. This reaction only occurs in the presence of a radiation field, and the rate of reaction is governed by the radiation flux and the concentrations of reactants.

Decomposition of H_2O_2

$$2\,H_2O_2 \rightarrow 2\,H_2O + O_2$$

This is a thermal decomposition reaction, independent of radiation flux. The peroxide "half-life" in reactor coolant is ~15 seconds. Decomposition also occurs on surfaces.

Corrosion reactions can consume O_2 and H_2O_2 (or produce H_2, in the absence of O_2 and H_2O_2). However, the rate of these reactions is very slow compared to the above reactions, and therefore they don't affect the concentration of H_2, O_2 and H_2O_2.

The above two reactions can be "summed" and simplified to:

$$2\,H_2O \leftrightarrow 2\,H_2 + O_2$$

Under normal water chemistry, there is a deficiency of hydrogen: the molar ratio of H_2/O_2 is <2. As hydrogen is added with feedwater, the molar ratio increases everywhere in the non-boiling regions downstream of the feedwater spargers. Once the ratio is raised to 2 at the feedwater spargers, it must be 2 everywhere else because the only chemical reaction that could change the ratio is the recombination reaction, $2\,H_2 + O_2 \longrightarrow 2\,H_2O$. This ratio removes 2 moles of hydrogen for every mole of O_2 consumed. So, at the H_2 injection rate that gives a mole ratio of exactly 2 at the feedwater spargers, the mole ratio will remain exactly 2 everywhere downstream.

Now, if slightly more hydrogen were added, the molar ratio would become slightly higher than 2 at the feedwater spargers. However, as the water flowed into the region of radiation flux, recombination reactions would occur. Since hydrogen is in excess, oxygen would be consumed and the ratio would increase, going to infinity as the oxygen (in the denominator) went to zero while there was still some excess hydrogen.

This can also be shown mathematically as follows. Assume for NWC (prior to hydrogen addition), the initial concentrations of hydrogen, oxygen and the molar ratio are:

$H_2 = H_2^{\mathbf{NWC}}$

$O_2 = O_2^{\mathbf{NWC}}$

Molar ratio $H_2^{\mathbf{NWC}}/O_2^{\mathbf{NWC}} < 2$

After hydrogen addition assume:

H_2 Added $= H_2^{\mathbf{ADD}}$

O_2 Consumed $= X$

Then H_2 Consumed $= 2X$

H_2/O_2 Ratio $= (H_2^{NWC} + H_2^{ADD} - 2X)/(O_2^{NWC} - X)$ **Equation A-1**

At the feedwater spargers, X = 0 (no radiation flux, no consumption of hydrogen or oxygen)

Determine $H_2^{\mathbf{ADD}}$ for H_2/O_2 Ratio = 2 at the feedwater spargers

$2 = (H_2^{\mathbf{NWC}} + H_2^{\mathbf{ADD}})/O_2^{\mathbf{NWC}}$

$H_2^{\mathbf{ADD}} = 2\,O_2^{\mathbf{NWC}} - H_2^{\mathbf{NWC}}$

Substitute into general expression for molar ratio, Equation A-1

H_2/O_2 Ratio $= (H_2^{\mathbf{NWC}} + 2\,O_2^{\mathbf{NWC}} - H_2^{\mathbf{NWC}} - 2X)/(O_2^{\mathbf{NWC}} - X)$

H_2/O_2 Ratio $= 2(O_2^{\mathbf{NWC}} - X)/(O_2^{\mathbf{NWC}} - X) = 2$

In other words, it doesn't matter what value of "X" is (i.e. how much oxygen has been consumed by recombination). The molar ratio remains "2" independent of where the water is.

Now, assume $H_2^{ADD} = 2\,O_2^{NWC} - H_2^{NWC} + H_2^{EXCESS}$ **Equation A-2**

Where $H_2^{\mathbf{EXCESS}}$ = the amount of H_2 over that needed for a 2/1 ratio

Substituting for H_2-ADD in Equation 1

$$H_2/O_2 \text{ Ratio} = (H_2^{\mathbf{NWC}} + 2\,O_2^{\mathbf{NWC}} - H_2^{\mathbf{NWC}} + H_2^{\mathbf{EXCESS}} - 2X)/(O_2^{\mathbf{NWC}} - X)$$

$$H_2/O_2 \text{ Ratio} = (2\,O_2^{\mathbf{NWC}} + H_2^{\mathbf{EXCESS}} - 2X)/(O_2^{\mathbf{NWC}} - X)$$

$$= 2(O_2^{\mathbf{NWC}} - X)/(\,O_2^{\mathbf{NWC}} - X) + H_2^{\mathbf{EXCESS}}/(\,O_2^{\mathbf{NWC}} - X)$$

$$= 2 + H_2^{\mathbf{EXCESS}}/(\,O_2^{\mathbf{NWC}} - X)$$

As “X” (the amount of oxygen consumed increases, the denominator of the “adder” term becomes smaller, the “adder” term increases, and the molar ratio goes >2.

B

NRC SAFETY EVALUATION OF BWRVIP-62: JANUARY 30, 2001

2001-023

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

January 30, 2001

Carl Terry, BWRVIP Chairman
Niagara Mohawk Power Company
Post Office Box 63
Lycoming, NY 13093

SUBJECT: SAFETY EVALUATION OF PROPRIETARY EPRI REPORT TR 108705, "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION (BWRVIP-62)" (TAC NO. MA4468)

Dear Mr. Terry:

The NRC staff has completed its initial review of the Electric Power Research Institute (EPRI) proprietary report TR-108705, "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)," dated December 1998. This report was submitted by letter dated December 31, 1998, for NRC staff review and approval.

The NRC staff, with assistance from the Argonne National Laboratory, has reviewed your submittal and finds, in the enclosed safety evaluation (SE), that the report requires additional information to be submitted. The BWRVIP-62 report brings together the physical chemistry information of several EPRI reports, but does not introduce any new data regarding the effect of fluence on irradiation assisted stress corrosion cracking (IASCC) crack growth rates. The proposed criteria for inspection relief are based on the crack growth rate model developed in EPRI TR-105873, which is limited to components with fluences $<5 \times 10^{20}$ n/cm^2. Although the report does make it clear that the 5×10^{20} n/cm^2 fluence level is a threshold to accelerated crack initiation and crack growth rate, it suggests that the effect of fluence at values higher than 5×10^{20} n/cm^2 may not be very great and that applicants for inspection relief in such cases should provide arguments on a case by case basis. However, it provides no guidance on developing the bases for this action.

The staff finds that, until additional data are available, the target threshold electrochemical corrosion potential (ECP) should remain at -230 mV. The staff also concludes that the noble metal chemical plating of stainless steel surfaces leads to a reduction in ECP in the presence of sufficient hydrogen. However, the staff requests that more detailed discussions be presented in the following areas: test facility design for flow effect on ECP and susceptibility, comparison of gamma dose rate (the G values) used in radiolysis model, validation of radiolysis model to predict water chemistries for a broader range of plants, and uncertainties in the hydrogen water chemistry (HWC) strategies.

The staff requests that you address the questions in the enclosed SE, as well as your response to other issues raised in the staff's SE, in a revised, final BWRVIP-62 report. Please inform the staff within 90 days of the date of this letter as to your proposed actions and schedule for such a revision.

Please contact C. E. (Gene) Carpenter, Jr., of my staff at (301) 415-2169, if you have any further questions regarding this subject.

Sincerely,

Jack Strosnider

Jack R. Strosnider, Director
Division of Engineering
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Enclosure: As stated

cc: See next page

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U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
SAFETY EVALUATION OF EPRI REPORT TR-108705, DECEMBER 1998, "BWRVIP VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION (BWRVIP-62)"

1.0 INTRODUCTION

1.1 Background

By letter dated December 31, 1998, as supplemented by letter dated March 7, 2000, the BWR Vessel and Internals Project (BWRVIP) submitted the Electric Power Research Institute (EPRI) report TR-108705, "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)", for staff review. The December 31, 1998, submittal, was a proprietary version of the report, while the March 7, 2000, submittal was the non-proprietary version of the report.

The BWRVIP requested that, based on the technical information of the report, the staff provide inspection relief for boiling water reactor (BWR) internal components. The request is based on a systematic methodology for evaluating the effectiveness of hydrogen water chemistry (HWC) for the mitigation of intergranular stress corrosion cracking (IGSCC) of reactor internals when direct measurements of the internals' corrosion potential is not feasible.

The BWRVIP-62 report contains a discussion of the justification for either inspection relief or credit for inspection of BWR internal components that are exposed to the less corrosive environment obtained through the application of moderate HWC (HWC-M) and Noble Metal Chemical Application (NMCA, previously noble metal chemical addition, or commercially as NobelChem™, a patented process of the General Electric Company, GE). Included in this justification are valid supplementary techniques that do not depend exclusively on direct measurement of the electrochemical corrosion potential (ECP) at specific locations to reliably demonstrate HWC effectiveness. The BWRVIP stated that their radiolysis/ECP model, developed and evaluated for over a decade, has been demonstrated to be in agreement with reliable chemistry measurements obtained from steam and recirculation piping at 23 BWRs, and is proposed in the BWRVIP-62 report to be an effective tool to monitor plant water chemistry/corrosion potential conditions.

1.2 Purpose

The staff reviewed the BWRVIP-62 report to determine whether the report provides acceptable levels of justification for inspection relief for BWR internal components susceptible to IGSCC. The review considered the role of fluence on IGSCC, crack propagation rate, physical chemistry aspects, effect of ECP, flow and NMCA on susceptibility, the radiolysis and ECP models, and an assessment of HWC effectiveness.

ENCLOSURE

1.3 Organization of the Report

This safety evaluation (SE) was written so as not to repeat proprietary information contained in the BWRVIP-62 report. The staff does not discuss in any detail the provisions of the guidelines not found in the non-proprietary version of the guidelines. A brief summary of the contents of the BWRVIP-62 report is given in Section 2.0 of this SE, with a detailed evaluation in Section 3.0. The conclusion is summarized in Section 4.0. The presentation of this evaluation is structured according to the organization of the BWRVIP-62 report.

2.0 SUMMARY OF BWRVIP-62 REPORT

The BWRVIP-62 report addresses the following topics in the following order:

- <u>Technical Basis for HWC Mitigation</u> - HWC and its effect on BWR IGSCC of the weld heat affected zone (HAZ) of type 304/316 stainless steel of reactor internal components, such as piping and the shroud, are discussed in conjunction with nickel based alloys like Alloy 600 and Alloy 182, which are also susceptible to IGSCC. A summary of the cracking events, a literature survey of the importance of the ionic impurities in the BWR coolant, and a survey of the mitigation methods, consisting of hydrogen addition to act as oxygen scavenger and noble metal addition which act as catalysts for hydrogen-oxygen recombination, are provided.

- <u>Radiolysis and ECP Models</u> - A discussion of ECP and the results of various reactor surveys are provided. Direct measurement is either difficult and/or inaccurate, therefore, use of the ECP relies on calculated values from modeling.

- <u>HWC Effectiveness Assessment</u> - The current operating history is reviewed and correlated to the corresponding plant water chemistry. It concludes that HWC is able to reduce crack initiation and crack growth. Methods are described using hydrogen injection and noble metal chemistry with hydrogen injection. All of the above are in combination with ECP measurements or calculations. The effect of HWC and the use of the noble metal chemistry on the N-16 radiation of the main steam line is discussed. The crack growth correlation developed in BWRVIP-14 (Reference 1) is used to develop expected factors of reduction in crack growth rate, corresponding to the expected reduction in ECP.

- <u>In-service Inspection Requirements</u> - The discussion of current in-service inspection requirements is provided and concludes that the HWC improvements would result in lower IGSCC propagation rates which would justify inspection relief.

3.0 EVALUATION

BWR austenitic stainless steel piping and reactor internal components have experienced IGSCC, leading to degradation and potential safety concerns. Therefore, regular inspections for BWR piping to provide adequate assurance of structural integrity of affected piping systems was found by the NRC staff to be necessary, as described in Generic Letter (GL) 88-01, "NRC Position on IGSCC in BWR Austenitic Stainless Steel Piping," dated January 25, 1988.

By letter dated October 27, 1999, as supplemented by letter dated February 29, 2000, the BWRVIP submitted the EPRI report TR-113932, "BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," for staff review. The BWRVIP-75 report proposed revisions to the extent and frequencies for piping inspection contained in GL 88-01. The proposed revisions were based on the consideration of inspection results and service experience gained by the industry since the issuance of GL 88-01, and included additional knowledge regarding the benefits of improved BWR water chemistry. The BWRVIP-75 report also provided justification for the proposed inspection criteria for Category A through E welds for the respective conditions of normal water chemistry (NWC) and HWC, making use of the criteria in the BWRVIP-62 report.

By letter dated September 15, 2000, the staff provided an initial SE regarding the BWRVIP-75 report, which contained several open items that the BWRVIP was requested to respond to. Included in these were Open Item 3.7, Reactor Water Coolant Conductivity, and Open Item 3.8, Effective HWC and NMCA Programs.

In Open Item 3.7, the staff recommended that, to qualify for the reduced inspection frequency, the average conductivity in reactor water coolant should not exceed the recommendations in the BWR Water Chemistry Guidelines, 1996 Revision (BWRVIP-29), or later revisions. The average conductivity can be calculated from the measurements made during the entire inspection interval based on the total operating time at a temperature at or above 200 °F.

In Open Item 3.8, the staff described several acceptance criteria that a licensee would need to meet in order that its HWC and NMCA programs be considered effective (i.e., qualifying for the reduced inspection schedule) for the subject piping. This Open Item also stated that a "more detailed discussion of the hydrogen vs. oxygen molar ratio will be provided in the staff's SE for the BWRVIP-62 report." This will be discussed further, below.

Inspections similar to those described in GL 88-01 may be needed for reactor internal components, and, for the safety-related internal components, the BWRVIP has defined a program of several inspection and flaw evaluation (I&E) guidelines that the staff has mostly reviewed and, with several modifications to address staff concerns, has found acceptable. However, due to the difficulty and expense of these self-imposed reactor internals inspections, licensees find it desirable to demonstrate that fewer inspections are necessary when suitable reactor internals IGSCC mitigation steps are taken.

The NRC has agreed that the environmental IGSCC mitigation technique, HWC combined with lower water conductivity, provides a basis for inspection relief for BWR recirculation piping (NRC letter to R. A. Pinelli, BWROG, "Safety Evaluation of Topical Report," NEDE-31951P, dated January 1995). Since the NRC established inspection relief criteria for recirculation piping with HWC, the HWC process has been developed along two parallel paths for mitigation of reactor internals IGSCC. The first qualified HWC technique for reactor internals involves higher hydrogen injection rates than would typically be used to protect recirculation piping. This process is referred as moderate HWC (HWC-M) and results in sufficient hydrogen addition to lower ECPs to protective levels in the lower plenum. The second protective technique involves the continuous injection of a small amount of hydrogen to give a hydrogen to oxygen molar ratio >2 in the single phase liquid region plus an occasional batch injection of catalytic noble metal compounds. This second process is referred to as noble metal chemical application (NMCA), formally known as noble metal chemical addition, and is also known by the GE trademark NobleChem™. Since both processes can protect BWR internals from environmental assisted cracking degradation, the effective implementation of either HWC-M or NMCA implementation at a BWR is considered in the BWRVIP-62 report to be an adequate basis for inspection relief for reactor internals.

Based on the crack growth modeling and radiolysis results, a vessel internals inspection program can be developed based on factors of improvement (FOI) for plants that have implemented either HWC-M or NMCA. The FOI calculated for each internal component based on modeling results would be applied to revise the internals inspection interval established in the various BWRVIP I&E reports. The BWRVIP will propose revised inspection intervals for vessel internals for plants that have implemented either HWC-M or NMCA at a later date.

The staff has completed its initial review of the BWRVIP-62 report, and finds that the guidance provided is generally acceptable, except for the below enumerated open items. The staff requests that BWRVIP review and resolve the open items raised below, and incorporate the staff's conclusions and recommendations into a revised BWRVIP-62 report.

Also, while not specifically listed below as an open item, the staff requests that the BWRVIP address, in this revision to the BWRVIP-62 report, how the technical basis of this report addresses the concerns that have arisen due to the leakage in the CRDM housing at Oyster Creek and Nine Mile Point Unit 1. In general, the staff requests that the BWRVIP discuss how HWC (and NMCA, as applicable), is effective in the lower head regions of the reactor vessel.

3.1 Irradiation Assisted Stress Corrosion Cracking (IASCC)

Open Item 3.1.1 The Role of Fluence

The BWRVIP-62 report recognizes the importance of fluence on crack growth; however, it does not present any new data, but rather references an older EPRI report, TR-107159, "Critical Issues Reviews for the Understanding and Evaluation of Irradiation Assisted Stress Corrosion Cracking," dated November 1996, (Reference 2) which has fluence data in the range of up to 5×10^{20} n/cm^2. Some BWR internal components have accumulated fluence in excess of this amount, and are projected to reach the range of 1×10^{22} n/cm^{22} before the end of life.

Regardless of the lack of data and the explicit statements made in BWRVIP-62 that the proposed models have not been validated for fluences above 5×10^{20} n/cm^2, the report recommends to the individual utilities that they should apply for inspection relief for higher fluences from the NRC on a case-by-case basis. This recommendation is based on the observation that there exists Swiss data which indicates that IASCC growth does not take place until fluence values reach the range of 8×10^{20} n/cm^2 to 1×10^{21} n/cm^2. The BWRVIP-62 report does not specify how the inspection relief request for operating plants for which components are above the 5×10^{20} n/cm^2 exposure level would be justified. Such conclusions are neither quantified or validated; therefore, this SE applies only to fluence values of less than or equal to 5×10^{20} n/cm^2. The BWRVIP should address this issue in a revision to the BWRVIP-62 report.

Open Item 3.1.2 Crack Propagation Rate

The crack propagation rate model is based on an empirical formula for crack growth rates developed in EPRI TR-105873, BWRVIP-14, (Reference 1) and based on a correlation of stress intensity, conductivity at 25 °C (77 °F), ECP, and absolute temperature in kelvin (K). Measured rates versus ECP indicate a relationship of increasing crack growth rate with increasing ECP values (as measured by a standard hydrogen electrode, SHE). However, the report does not introduce fluence as a variable and the question of crack propagation rate at fluences at or above 5 x 10^{20} n/cm^2 is not dealt with. The BWRVIP should provide a technical justification for not using fluence as a variable, and should address this issue in a revision to the BWRVIP-62 report.

Open Item 3.2 Physical Chemistry Aspects of the Inspection Relief Request

The NRC staff, with the assistance from the Argonne National Laboratory (ANL), has reviewed the physical chemistry aspects of the inspection relief request. The key elements of the BWRVIP-62 report reviewed include the following: effect of ECP on susceptibility, flow effect on ECP and susceptibility, NMCA, radiolysis model, ECP model, and assessment of HWC effectiveness.

The staff has given inspection relief for the use of HWC mitigation measures for BWR stainless steel piping, four inches or greater in diameter, documented in the staff's initial safety evaluation for BWRVIP-75 (Reference 3). Credit for improvement for HWC and NMCA are given in the Table titled "Summary of Staff Proposed Modifications to BWRVIP-75." The table has incorporated separate degrees of inspection relief for the use HWC and for NMCA. The BWRVIP-75 Report uses the BWRVIP-62 report as a technical basis document for a systematic methodology for evaluating the effectiveness of HWC, with or without NMCA for the mitigation of IGSCC.

The staff has defined an "effective" HWC and NMCA program in Open Item 3.8 of the staff's SER on the BWRVIP-75 report. The elements of an "effective" (i.e., qualifying for a reduced inspection schedule) program are taken from the staff's position on BWRVIP-75 Open Item 3.8 and are repeated here:

For effective HWC programs, the ECP measurements should be -230 mV or less and be measured by at least two different reference electrodes. Alternately, secondary parameters may be monitored regularly to verify the effectiveness of HWC, when direct measurements are not available. HWC should be available at least 80 percent of the time. Conductivity transients (>0.3 uS/cm) of less than 24 hours need not be subtracted from the acceptable HWC service time. When the hydrogen injection is interrupted for less than 10 hours, the interrupt time need not be excluded from the calculation of the acceptable HWC service time as long as the ECP is below -230 mV or the secondary parameter meet the acceptance criteria.

For an acceptable NMCA program the hydrogen vs. oxygen molar ratio should be 4:1 and above; there should be a monitoring program to determine if the NMCA remains applied and to determine when the process needs to be re-applied; NMCA is only applicable when HWC is available, and should be available at greater than 90 percent of the hot operating time; conductivity transients (>0.3 uS/cm) lasting 24 hours or less, need not be subtracted from the acceptable NMCA service time.

Conformance to the above criteria should be addressed in a revision to the BWRVIP-62 report.

Open Item 3.2.1 Effect of ECP on Susceptibility

Many investigators have shown a strong dependence of IGSCC susceptibility and crack growth rate (CGR) on the ECP of stainless steels in BWR environments. The BWR Water Chemistry Guidelines - 1996 Revision (BWRVIP-29), and the latest revision, BWRVIP-79, dated March 2000) have incorporated -230 mV as the "protection potential" for IGSCC of thermally sensitized steels based on in-reactor slow strain rate tests. However, the BWRVIP-62 report indicates that the threshold ECP for IGSCC initiation in irradiated Type 304 stainless steel may be as high as -140 mV, based on the work of Indig, et al. The staff finds this conclusion to be unjustified. The -140 mV threshold is based on limited data. In addition, the "threshold" potential would be a function of the following: irradiation level, concentrations of impurities in the coolant, and the microstructure and composition of the steel. One would expect a fairly wide range of "threshold" potentials and the -140 mV value may represent a unique case.

The staff position is that, until additional data are available, the target threshold ECP should remain at -230 mV. This should be addressed in a revision to the BWRVIP-62 report.

Open Item 3.2.2 Flow Effect on ECP and Susceptibility

Under BWR NWC conditions, the oxidation and reduction reactions on passive steel surfaces are limited by the mass transport of oxygen to the surface for the oxygen reduction reaction. Mass transport increases as flow increases and, thus, ECP is expected to increase with flow velocity. However, this ECP increase does not necessarily lead to an increase in susceptibility. Surface characteristics of tested specimens have shown that increased flow leads to a reduction in susceptibility for smooth surfaces and that greater surface roughness reduced the convective flows within the crack. The BWRVIP-62 report argues that the effect of flow is to move the "effective" mouth of the crack down the crack. This is based on the assumption that the convection forces penetrate far enough into the crack that the bulk concentration of impurities is maintained until the ECP decreases to a low level. Direct evidence of this phenomenon is limited. Tests performed by GE showed that, although ECP increased significantly with flow rate, the CGR decreased.

The staff requests that a more detailed description of these tests be provided.

Open Item 3.2.3 Noble Metal Chemical Application / Additions (NMCA)

BWR coolant oxygen reduction and hydrogen oxidation are assumed to be the most dominant reactions on most metal surfaces. The rates of these reactions are dependent on the ECP, which is determined by measuring the overall balance of charge. Tests have shown that materials with catalytic coatings exhibit the low crack growth rates normally associated with low ECPs, even though the nominal water chemistry in the test had high levels of dissolved oxygen and impurities. This process has been successful in preventing IGSCC in slow strain rate tests, which represent more severe loading conditions than would be expected in the reactor. In addition, long term laboratory tests and in-reactor testing indicate that the coatings remain effective for significant periods of time. The staff agrees that the plating of stainless steel surfaces with noble metals leads to a reduction in ECP in the presence of sufficient hydrogen, and agrees in general with the BWRVIP-62 report on the advantages of NMCA. However, the

BWRVIP-62 report needs to be modified to clarify that, for an acceptable NMCA program, the hydrogen vs. oxygen molar ratio should be 4:1 and above, as stated above.

Open Item 3.2.4 Radiolysis Model

For the past ten years, the radiolysis model has undergone many changes. These changes include refinement of the description of the primary system, dose rate modeling of the ex-core regions and updating of the neutron/gamma dose rates (the G values). The staff requests a discussion on the significant differences between the BWRVIP-62 report, G values and those used in similar approaches in Taiwan and Japan (References 5 and 6) to analyze the impact of hydrogen water chemistry.

The staff also requests that results from a broader range of plants be included in a revised BWRVIP-62 report in order to validate the capability of the model to predict water chemistries. Although numerous correlations of in-plant measurements are given in Figures 3-1 to 3-11 of the BWRVIP-62 report, comparative model results in the referenced Appendix A of BWRVIP-13 (Reference 7) are not presented in terms of the proposed secondary parameters. Because of this difference, it is impossible to determine that the model results represent the range of behavior observed in-reactor.

Open Item 3.2.5 ECP Model

The ECP model in the BWRVIP-62 report is an empirical correlation relating concentrations of H_2, O_2, H_2O_2, and flow velocity to ECP. The results of six plants are presented in Figure 2.8 of the proprietary version of the BWRVIP-62 report. However, when grouped by plant, the data does not appear to be randomly distributed about the mean trend line. The individual plant data appears to cluster above or below the trend line, which would indicate that ECP cannot be simply estimated on the basis of the standard deviation based on the whole population of data. In addition, the staff notes that ECP models implicitly assume that the experimental measurements are correct. However, more extensive efforts to resolve discrepancies between multiple measurements of ECP need to be undertaken. This should be addressed in a revision to the BWRVIP-62 report.

Open Item 3.2.6 Assessment of HWC Effectiveness

The overall presentation of the strategies for monitoring the effectiveness of hydrogen water chemistries presented is adequate. However, almost all radiolysis analyses have shown that radiation levels in the downcomer region have a strong effect on the rate of hydrogen-oxygen recombination reaction. Since this radiation level in the downcomer varies throughout core life, the actual degree of mitigation achieved will also vary. The staff requests a discussion on the details or criteria to address uncertainties in the degree of mitigation associated with the change in radiation levels.

4.0 CONCLUSION

The staff with the assistance of Argonne National Laboratory reviewed the EPRI TR-108705, topical report on "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)". The BWRVIP-62 report brings together the physical chemistry information of several EPRI reports, but does not introduce any new data regarding the effect of fluence on IASCC crack growth rates. The proposed criteria for inspection relief are based on the crack growth rate model developed in EPRI TR-105873 (BWRVIP-14) and therefore any conclusions in this SE are limited to components with fluences less than or equal to 5 x 10^{20} n/cm^2.

The staff finds that, until additional data are available, the target threshold ECP remain at −230 mV. The staff also concluded that the noble metal plating of stainless steel surfaces leads to a reduction in ECP in the presence of sufficient hydrogen. However, the staff requests that more detailed discussions be presented in the following areas: the test for flow effect on ECP and susceptibility, comparison of G values used in radiolysis model, validation of radiolysis model to predict water chemistries for a broader range of plants, and uncertainties in the HWC strategies.

The BWRVIP, in the subject report, proposes no quantitative revised inspection schedules and indicates this will be done at a later date; therefore, the staff makes no finding on the degree of relief justified over current inspection schedules at this time.

5.0 References

1. BWR Vessels and Internals Project, "Evaluation of Crack Growth in BWR Stainless Steel RPV Internals (BWRVIP-14)", EPRI TR-105873, Electric Power Research Institute, Palo Alto (1996).

2. EPRI report TR-107159, "Critical Issues Reviews for the Understanding and Evaluation of Irradiation Assisted Stress Corrosion Cracking," dated November 1996.

3. Letter from Jack R. Strosnider, USNRC, to Carl Terry, BWRVIP, Safety Evaluation of the "BWRVIP Vessel and Internals Project, BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," EPRI Report TR-113932, September 15, 2000.

4. BWR Vessels and Internals Project, "Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)", EPRI TR-113932, Electric Power Research Institute, Palo Alto CA, October 1999.

5. T. K. Yeh, M. S. Yu, C.P. Wang, F. Chu, C. S. Huang, J. T. Kao, "A Comparitive Study of the Effectiveness of Hydrogen Water Chemistry by Computer Modeling for Chinsan and Kuosheng, *"Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL (1997).

6. Y. Wada, N Shigenaka, N. Uetake, S. Uchida, "Numerical Simulation of SCC Environment in a BWR Primary Coolant System, *"Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL (1997).

7. EPRI TR-106068, "Modeling Hydrogen Water Chemistry for BWR Applications - New Results (BWRVIP-13), Electric Power Research Institute, Palo Alto, CA (1995)

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BWRVIP RESPONSE TO NRC SAFETY EVALUATION OF BWRVIP-62: AUGUST 1, 2001

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BWRVIP BWR Vessel & Internals Project 2001-250

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August 1, 2001

Document Control Desk
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: C. E. Carpenter

Subject: PROJECT NO. 704 – BWRVIP Response to NRC Safety Evaluation of BWRVIP-62

Reference:
1. Letter from Jack R. Strosnider (NRC) to Carl Terry (BWRVIP Chairman), "Safety Evaluation of Proprietary EPRI Report TR 1087805, BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62) (TAC NO. MA4468)," dated January 30, 2001.
2. Letter from Carl Terry (BWRVIP Chairman) to NRC Document Control Desk, "PROJECT NO. 704 – BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), EPRI Report TR-108705, December 1998," dated December 31, 1998.

Enclosed are ten (10) copies of the BWRVIP response to the issues identified in the NRC Safety Evaluation of the BWRVIP report "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)" that was transmitted by the Reference 1 letter identified above.

The enclosed document contains proprietary information. Therefore, the request to withhold the BWRVIP-62 report from public disclosure transmitted to the NRC by the Reference 2 letter identified above also applies to the enclosed document.

If you have any questions on this subject, please contact John Wilson of AmerGen (BWRVIP Mitigation Committee Technical Chairman) by telephone at 217.937.4354.

Sincerely,

CTerry

Carl Terry
Niagara Mohawk Power Corp.
Chairman, BWR Vessel and Internals Project

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BWRVIP Response to Issues in NRC Safety Evaluation of "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)," EPRI TR-108705, January 30, 2001

Below are the issues identified in the January 30, 2001 NRC Safety Evaluation (SE) of the proprietary EPRI report TR-108705, "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)," followed by the BWRVIP response to each issue. The BWRVIP proposes to incorporate staff comments and other changes, where applicable, in the BWRVIP-62 report.

Open Item 3.1.1 Role of Fluence

The BWRVIP-62 report recognizes the importance of fluence on crack growth; however, it does not present any new data, but rather references an older EPRI report, TR-107159, "Critical Issues Reviews for the Understanding and Evaluation of Irradiation Assisted Stress Corrosion Cracking," dated November 1996, (Reference 1-14 in BWRVIP-62) which has fluence data in the range of up to 5×10^{20} n/cm^2. Some BWR internal components have accumulated fluence in excess of this amount, and are projected to reach the range of 1×10^{22} n/cm^2 before the end of life.

Regardless of the lack of data and the explicit statements made in BWRVIP-62 that the proposed models have not been validated for fluences above 5×10^{20} n/cm^2, the report recommends to the individual utilities that they should apply for inspection relief for higher fluences from the NRC on a case-by-case basis. This recommendation is based on the observation that there exists Swiss data, which indicates that IASCC growth does not take place until fluence values reach the range of 8×10^{20} n/cm^2 to 1×10^{21} n/cm^2. The BWRVIP-62 report does not specify how the inspection relief request for operating plants for which components are above the 5×10^{20} n/cm^2 exposure level would be justified. Such conclusions are neither quantified nor validated; therefore, this SE applies only to fluence values of less than or equal to 5×10^{20} n/cm^2. The BWRVIP should address this issue in a revision to the BWRVIP-62 report.

Response to Open Item 3.1.1. It is anticipated that there will be IGSCC mitigation with HWC/NMCA based on the current state of knowledge, i.e., there will also be a factor of improvement (FOI) at high fluences. However, at this time the BWRVIP is only requesting inspection credit for welds that have a fluence less than 5×10^{20} n/cm^2

BWRVIP will address crack growth rates for fluences greater than 5×10^{20} n/cm^2 for both NWC and HWC environments in a separate BWRVIP report to be submitted to the NRC later in 2001.

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Open Item 3.1.2 Crack Propagation Rate

The crack propagation rate model is based on an empirical formula for crack growth rates developed in EPRI TR-105873, BWRVIP-14 and based on a correlation of stress intensity, conductivity at 25 °C (77 °F), ECP, and absolute temperature in Kelvin (K). Measured rates versus ECP indicate a relationship of increasing crack growth rate with increasing ECP values (as measured by a standard hydrogen electrode, SHE). However, the report does not introduce fluence as a variable and the question of crack propagation rate at fluences at or above 5×10^{20} n/cm^2 is not dealt with. The BWRVIP should provide a technical justification for not using fluence as a variable, and should address this issue in a revision to the BWRVIP-62 report.

Response to Open Item 3.1.2: This response is identical to 3.1.1. It is anticipated that there will be IGSCC mitigation with HWC/NMCA based on the current state of knowledge, i.e., there will also be a factor of improvement (FOI) at high fluences. However at this time the BWRVIP is only requesting inspection credit for welds that have a fluence less than 5×10^{20} n/cm^2. The BWRVIP will address crack growth rates for fluences greater than 5×10^{20} n/cm^2 for both NWC and HWC environments in a separate BWRVIP report to be submitted to the NRC later in 2001.

Open Item 3.2 Physical Chemistry Aspects of the Inspection Relief Request

The NRC staff, with the assistance from the Argonne National Laboratory (ANL), has reviewed the physical chemistry aspects of the inspection relief request. The key elements of the BWRVIP-62 report reviewed include the following: effect of ECP on susceptibility, flow effect on ECP and susceptibility, NMCA, radiolysis model, ECP model, and assessment of HWC effectiveness.

The staff has given inspection relief for the use of HWC mitigation measures for BWR stainless steel piping, four inches or greater in diameter, documented in the staff's initial safety evaluation for BWRVIP-75. Credit for improvement for HWC and NMCA are given in the Table titled "Summary of Staff Proposed Modifications to BWRVIP-75." The table has incorporated separate degrees of inspection relief for the use HWC and for NMCA. The BWRVIP-75 Report uses the BWRVIP-62 report as a technical basis document for a systematic methodology for evaluating the effectiveness of HWC, with or without NMCA for the mitigation of IGSCC.

The staff has defined an "effective" HWC and NMCA program in Open Item 3.8 of the staff's SER on the BWRVIP-75 report. The elements of an "effective" (i.e., qualifying for a reduced inspection schedule) program are taken from the staff's position on BWRVIP-75 Open Item 3.8 and are repeated here:

For effective HWC programs, the ECP measurements should be -230 mV or less and be measured by at least two different reference electrodes. Alternately, secondary parameters may be monitored regularly to verify the effectiveness of HWC, when direct measurements are not available. HWC should be available at least 80 percent of the time.

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Conductivity transients (>0.3 µS/cm) of less than 24 hours need not be subtracted from the acceptable HWC service time. When the hydrogen injection is interrupted for less than 10 hours, the interrupt time need not be excluded from the calculation of the acceptable HWC service time as long as the ECP is below -230 mV or the secondary parameter meet the acceptance criteria.

For an acceptable NMCA program the hydrogen vs. oxygen molar ratio should be 4:1 and above; there should be a monitoring program to determine if the NMCA remains applied and to determine when the process needs to be re-applied; NMCA is only applicable when HWC is available, and should be available at >90 percent of the hot operating time; conductivity transients (>0.3 µS/cm) lasting 24 hours or less, need not be subtracted from the acceptable NMCA service time.

Conformance to the above criteria should be addressed in a revision to the BWRVIP-62 report.

<u>Response to Open Item 3.2:</u> The BWRVIP agrees with the NRC that certain water chemistry parameters should be monitored in order to maintain an effective HWC program. As noted in BWRVIP-62, effective HWC does include injection of hydrogen alone or in combination with NMCA. Furthermore, BWRVIP-62 provides extensive guidance that a licensee can use to maintain effective HWC and NMCA programs. Therefore, the BWRVIP is confident that compliance with BWRVIP-62 as described in Section 3.3 of BWRVIP-62 assures adequate protection of the internals and provides a technical basis for revisions to the inspection frequency in the future.

A. Open Item 3.2 Paragraph 4 (Effective HWC Program):
The BWRVIP agrees with the NRC that monitoring of ECP and secondary parameters is appropriate. This is clearly documented in Table 3-5 of BWRVIP-62. The BWRVIP proposes to incorporate the following changes in BWRVIP-62 regarding an effective HWC program:

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B. Open Item 3.2 Paragraph 5 (Acceptable NMCA Program):

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The BWRVIP has the following additional comments regarding an effective NMCA program.

The BWRVIP agrees that for NMCA to be effective, hydrogen must be injected. As noted in the response to Open Item 3.2 Paragraph 4, the BWRVIP agrees with the staff position that 80% availability at an ECP of -230 mV guarantees effective HWC. For periods of equal availability, the use of hydrogen with NMCA is equivalent to that of hydrogen alone if both achieve an ECP of -230 mV(SHE). Therefore, the acceptable level of availability should not be dependent on the method used to achieve effective HWC.

However, we continue to believe that these values do not represent an absolute threshold such that if neither one is achieved, HWC is no longer beneficial. Data presented in Figure 4-1 of BWRVIP-62 show that the reduction in crack growth rate by HWC can be conservatively determined through a combination of ECP and availability. Any lowering of ECP from Normal Water Chemistry values provides some benefit in reducing crack growth rate Therefore, the BWRVIP believes there is sufficient technical basis to determine the benefit of HWC using the factor of improvement (FOI) approach described in Sections 4.2 and 4.3 of BWRVIP-62.

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Open Item 3.2.1. Effect of ECP on Susceptibility

Many investigators have shown a strong dependence of IGSCC susceptibility and crack grown rate (CGR) on the ECP of stainless steels in BWR environments. The BWR Water Chemistry Guidelines - 1996 Revision (BWRVIP-29), and the latest revision, BWRVIP-79, dated March 2000 have incorporated -230 mV (vs. the standard hydrogen electrode or SHE) as the "protection potential" for IGSCC of thermally sensitized steels based on in-reactor slow strain rate tests. However, the BWRVIP-62 report indicates that the threshold ECP for IGSCC initiation in irradiated Type 304 stainless steel may be as high as -140 mV, based on the work of Indig, et al. The staff finds this conclusion to be unjustified. The -140 mV threshold is based on limited data. In addition, the "threshold" potential would be a function of the following: irradiation level, concentrations of impurities in the coolant, and the microstructure and composition of the steel. One would expect a fairly wide range of "threshold" potentials and the -140 mV value may represent a unique case.

The staff position is that, until additional data are available, the target threshold ECP should remain at -230 mV. This should be addressed in a revision to the BWRVIP-62 report.

Response to Open Item 3.2.1: The BWRVIP accepts the NRC position that the target threshold of ECP for IGSCC initiation should remain less than or equal to -230 mV for irradiated stainless steels pending the development of additional data.

Open Item 3.2.2 Flow Effect on ECP and Susceptibility:

Under BWR NWC conditions, the oxidation and reduction reactions on passive steel surfaces are limited by the mass transport of oxygen to the surface for the oxygen reduction reaction. Mass transport increases as flow increases and, thus, ECP is expected to increase with flow velocity. However, this ECP increase does not necessarily lead to an increase in susceptibility. Surface characteristics of tested specimens have shown that increased flow leads to a reduction in susceptibility for smooth surfaces and that greater surface roughness reduced the convective flows within the crack. The BWRVIP-62 report argues that the effect of flow is to move the "effective" mouth of the crack down the crack. This is based on the assumption that the convection forces penetrate far enough into the crack that the bulk concentration of impurities is maintained until the ECP decreases to a low level. Direct evidence of this phenomenon is limited. Test performed by GE showed that, although ECP increased significantly with flow rate, the CGR decreased. The staff requests that a more detailed description of these tests be provided.

Response to Open Item 3.2.2: BWRVIP will provide the NRC with "BWR Vessel and Internals Project, Effect of Flow Rate on Intergranular Stress Corrosion Cracking and Electrochemical Corrosion Potential (BWRVIP-64)," EPRI Report TR-112314, March 1999. This report will provide the NRC with a complete and more detailed description of the tests.

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Open Item 3.2.3 Noble Metal Chemical Application / Additions (NMCA)

BWR coolant oxygen reduction and hydrogen oxidation are assumed to be the most dominant reactions on most metal surfaces. The rates of these reactions are dependent on the ECP, which is determined by measuring the overall balance of charge. Tests have shown that materials with catalytic coatings exhibit the low crack growth rates normally associated with low ECPs, even though the nominal water chemistry in the test had high levels of dissolved oxygen and impurities. This process has been successful in preventing IGSCC in slow strain rate tests, which represent more severe loading conditions than would be expected in the reactor. In addition, long-term laboratory tests and in-reactor testing indicate that the coatings remain effective for significant periods of time. The staff agrees that the plating of stainless steel surfaces with noble metals leads to a reduction in ECP in the presence of sufficient hydrogen, and agrees in general with the BWRVIP-62 report on the advantages of NMCA. However, the BWRVIP-62 report needs to be modified to clarify that, for an acceptable NMCA program, the hydrogen vs. oxygen molar ratio should be 4:1 and above, as stated above.

Response to Open Item 3.2.3: Based on ECP data from NMCA plants that became available after BWRVIP-62 was submitted, the BWRVIP now considers that a hydrogen vs. oxygen molar ratio of 2 is acceptable and that a molar ratio of 4 is not essential to ensure mitigation of plant components. The BWRVIP recognizes that a plant needs to provide a margin in the hydrogen injection rate to achieve the molar ratio of 2. However, if the molar ratio is too high it could result in increased main steam line radiation fields because of N-16 carry over. Therefore the molar ratio should be optimized to ensure protection and to minimize N-16 carry over. The following data demonstrates that a molar ratio of 2 will be adequate to ensure protection.

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molar ratio in reactor water as indicated in Table 3-5 of BWRVIP-62 will provide verification of mitigation.

Open Item 3.2.4 Radiolysis Model

For the past ten years, the radiolysis model has undergone many changes. These changes include refinement of the description of the primary system, dose rate modeling of the ex-core regions and updating of the neutron/gamma docs rates (the G values). The staff requests a discussion on the significant differences between the BWRVIP-62 report, G values and those used in similar approaches in Taiwan and Japan (References 5 and 6) to analyze the impact of hydrogen water chemistry.

The staff also requests that results from a broader range of plants be included in a revised BWRVIP-62 report to validate the capability of the model to predict water chemistries. Although numerous correlations of in-plant measurements are given in Figures 3-1 to 3-11 of the BWRVIP-62 report, comparative model results in the referenced Appendix A of BWRVIP-13 (Reference 7) are not presented in terms of the proposed secondary parameters. Because of this difference, it is impossible to determine that the model results represent the range of behavior observed in-reactor.

Response to Open Item 3.2.4 The G values and reaction rate constants and some of the radiolysis schemes in the EPRI model were based on the state of the art in late 1980s. At that time the integrated set of constants gave the best correlation of plant measurements. It was recognized that model inputs have a range of uncertainties that would result in uncertainties in predictions. The approach to address these uncertainties was to compare the model predictions of hydrogen, oxygen and ECP at specific locations to plant measurements of the same parameters at the same locations. These comparisons are discussed in Section 2.3 (pages 2-14 to 2-16) of BWRVIP-62 and summarized in the following paragraphs. The results reported in BWRVIP-62 were developed based on the current (1998) version of the BWRVIP radiolysis/ECP model (BWRVIA Version 1.0). This is a later version of the model compared to the one that was used to prepare BWRVIP-13 in 1995.

It should be noted that while the model calculates oxygen, hydrogen and ECP throughout the plant, most actual in-plant measurements are made of oxygen and hydrogen concentrations in the reactor water. A few plants have also measured hydrogen and oxygen in steam. Reactor water oxygen and hydrogen and steam oxygen are also listed as secondary parameters in Table 3-5 of BWRVIP-62.

Figures 2.4 and 2.5 in BWRVIP-62 show a comparison of measured and calculated steam hydrogen and steam oxygen data for three plants. Similarly, Figures 2.6 and 2.7 show the calculated and measured hydrogen and oxidant data in the recirculation system for four plants.

Figure 3 presents recent data from Susquehanna-2 comparing chemistry measurements to model predictions (Reference 1). Again there is good agreement between the measured

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oxygen in the reactor water and that predicted by the model. Similarly there is close agreement between the measured and predicted hydrogen in the reactor water.

The comparisons of model predictions of hydrogen and oxygen versus plant measurements show that the BWRVIA radiolysis ECP model is in good agreement with chemistry measurements for reactor water and steam systems. The comparisons cover a range of BWR types, core power outputs, core radius and power densities as shown in Table 2.

Table 2: BWR Plants Used in BWRVIA Model vs.
Chemistry/ECP Comparisons

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Figure 2.8 of BWRVIP-62 shows a comparison of ECP calculated by the model versus plant ECP measurements at mid-core, core plate, recirculation flange and drain line at six plants. The scatter about the best-fit line is approximately = /. The revised BWRVIP-62 will include additional ECP data from Susquehanna and Garoña that were not available when Figure 2.8 was developed. These data are discussed below.

Figure 4 shows a comparison of ECP measurements and model calculations below the core plate at Susquehanna-1 during Cycle 11 HWC startup (Reference 1 below). The model predictions and plant measurements show reasonable agreement. The model predictions of ECP are conservative compared to measurements at this location.

Figure 5 presents ECP data from probes located in the lower vessel head region at Susquehanna-2. In this location the BWRVIP model underestimated the hydrogen injection rate required to achieve protection (-230 mV) by approximately = . The ECP data and model showed better agreement at hydrogen concentrations equal to or greater than 1.6 ppm. For this plant the ECP model was more accurate in the core plate region than in the lower vessel head region.

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Subsequent to the development of the current version of the model there have been experiments and research conducted to quantify the fundamental chemical-physical constants and reaction schemes. BWRVIP is planning to evaluate the recent data on G values and reaction rate constants as well as the ECP correlation to further refine the model and reduce uncertainties in the model predictions particularly in the lower vessel head region. The planned work will include a review of the G values used in the two NRC references cited below. Currently BWRVIP does not have sufficient information to comment on the radiolysis ECP models discussed in these two publications.

Therefore, based on the above discussion, the BWRVIP believes that the current BWRVIA model shows good agreement with plant chemistry data as well as plant ECP data at specific locations. Additional work is planned to reduce the observed ECP uncertainties in the lower plenum region.

T. K. Yeh, M. S. Yu, C. P. Wang, F. Chu, C. S. Huang, J. T. Kao, "A Comparative Study of the Effectiveness of Hydrogen Water Chemistry by Computer Modeling for Chinshan and Kuosheng, "*Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, American Nuclear Society, La Grange Park, IL (1997).

Y. Wada, N. Shigenaka, N. Uetake, S. Uchida, "Numerical Simulation of SCC Environment in a BWR Primary Coolant System, "*Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, American Nuclear Society, La Grange Park, IL (1997).

Reference 1: D. J. Morgan and H. T. Tang, "Radiolysis and ECP Analysis of Susquehanna Unit 1 and 2 Using BWRVIA", ICONE 9, Nice, France, April 8-12, 2001.

Open Item 3.2.5 ECP Model

The ECP model in the BWRVIP-62 report is an empirical correlation relating concentrations of H_2, O_2, H_2O_2, and flow velocity to ECP. The results of six plants are presented in Figure 2.8 of the proprietary version of the BWRVIP-62 report. However, when grouped by plant, the data does not appear to be randomly distributed about the mean trend line. The individual plant data appears to cluster above or below the trend line, which would indicate that ECP cannot be simply estimated on the basis of the standard deviation based on the whole population of data. In addition, the staff notes that ECP models implicitly assume that the experimental measurements are correct. However, more extensive efforts to resolve discrepancies between multiple measurements of ECP need to be undertaken. This should be addressed in a revision to the BWRVIP-62 report.

<u>Response to Open Item 3.2.5: Moderate HWC Plants (Category 1):</u> The ECP probes provide by GE are qualified by test to measure withir ═) millivolts of the theoretically calculated potential in simulated BWR primary water. Multiple probes of different types (for example, platinum and iron/iron oxide) are typically installed together, and the highest ECP indication is used to determine HWC effectiveness. Therefore, the BWRVIP does not believe it necessary to apply a correction factor to in-plant ECP measurements. Plants on moderate HWC that use measured ECP as a primary parameter, i.e., Category 1 in Table 3-5, shall derive a correlation between measured ECP and calculated total oxidant (O_2 ppb+ ½ H_2O_2 ppb) at that location for that plant. The BWRVIA model will be used to calculate the total oxidant. If the total oxidant calculated at other plant locations is less than the concentration that correlates with an ECP of –230 mV(SHE), then effective mitigation is assured at those locations.

In addition, secondary parameters in Table 3-5 will be used to confirm that effective HWC is being maintained. It is proposed that for plants on moderate HWC at least two secondary parameter: **Content Deleted EPRI Proprietary** d **Content Deleted EPRI Proprietary**) will be measured to verify protection.

<u>Response to Open Item 3.2.5: Moderate HWC Plants (Category 2):</u> The NRC acceptance of plants on moderate HWC that use estimated ECP from the Radiolysis/ECP model as the primary parameter (Category 2 in Table 3-5) is contingent on review and acceptance of the BWRVIA radiolysis ECP model on a plant specific basis. These plants shall use the following approaches to derive ECP.

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<u>Response to Open Item 3.2.5:</u>

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Open Item 3.2.6 Assessment of HWC Effectiveness

The overall presentation of the strategies for monitoring the effectiveness of hydrogen water chemistries presented is adequate. However, almost all radiolysis analyses have shown that radiation levels in the downcomer region have a strong effect on the rate of hydrogen-oxygen recombination reaction. Since this radiation level in the downcomer varies throughout core life, the actual degree of mitigation achieved will also vary. The staff requests a discussion on the details or criteria to address uncertainties in the degree of mitigation associated with the change in radiation levels.

Response to Open Item 3.2.6: The licensees will use the radiolysis/ECP model for both the beginning and end of life of a fuel cycle. The end of the fuel cycle should represent the most conservative case, i. e., there should be an elevation in ECP at the end of the cycle.

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Table 3-5 (Revised): Example of Primary and Secondary Parameters for BWR HWC/NMCA Categories

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Figure 1: ECP vs. feedwater hydrogen response of NMCA treated BWRs

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Figure 2: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for FitzPatrick. (By: Core bypass, PM: Mixing plenum, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPb: Lower plenum bottom, LPt: Lower plenum top)

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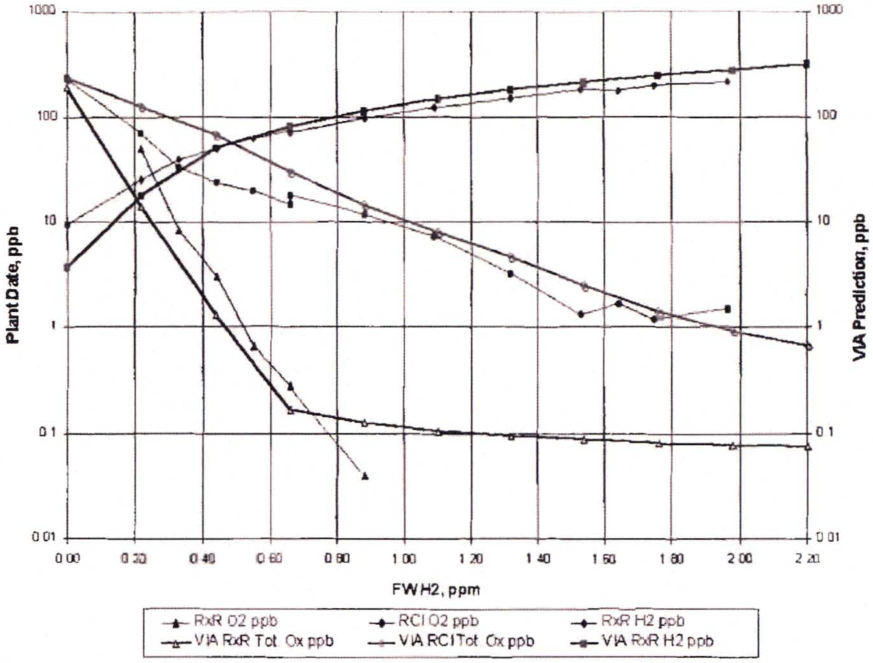

Figure 3. SSES-2 HWC Startup Chemistry vs. BWRVIA Predictions
RxR – Reactor Recirculation Sample
RCI – Reactor Water Cleanup Inlet Sample
VIA – BWRVIA Radiolysis Model Prediction

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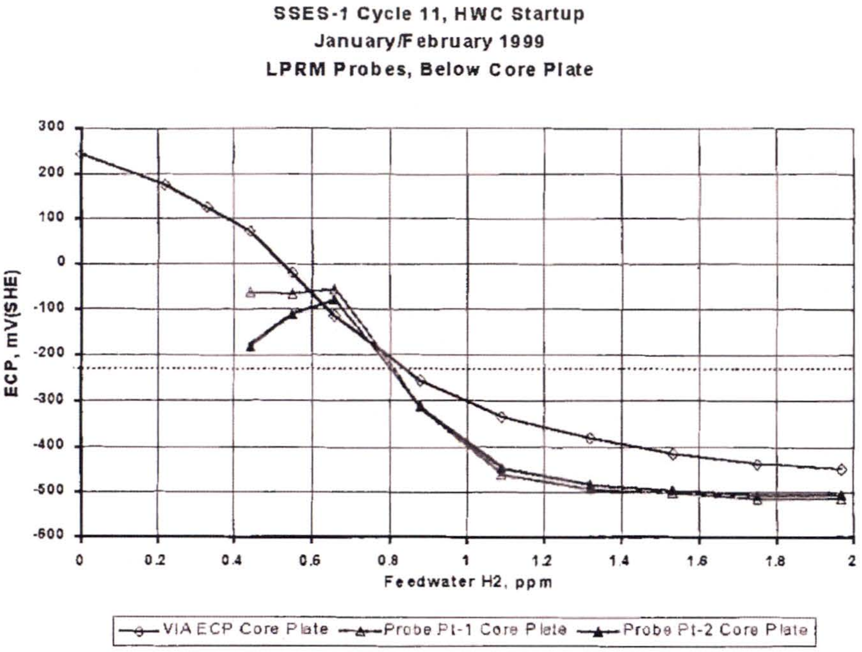

Figure 4. Predicted and Measured ECP below the Core Plate, SSES-1
VIA – BWRVIA Radiolysis Model Prediction

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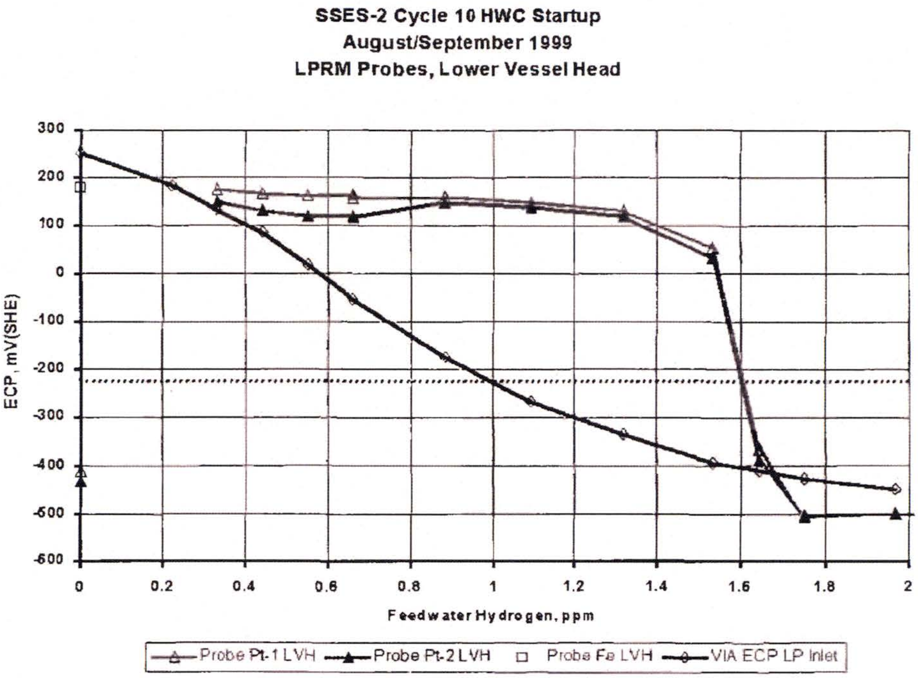

SSES-2 Cycle 10 HWC Startup
August/September 1999
LPRM Probes, Lower Vessel Head

Figure 5. Predicted and Measured ECP in the Lower Vessel Head, SSES-2
VIA – BWRVIA Radiolysis Model Prediction
LVH – Lower Vessel Head Region
LP Inlet – Lower Plenum Inlet, Predicted ECP at Probe Location

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Figure 6: Comparison of Calculated and Measured ECP Values

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SUPPLEMENT TO BWRVIP RESPONSE TO NRC SAFETY EVALUATION OF BWRVIP-62: MAY 19, 2003

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BWRVIP BWR Vessel & Internals Project 2003-149

May 19, 2003

Document Control Desk
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Meena Khanna

Subject: PROJECT NO. 704 – Supplement to the BWRVIP Response to Issues in NRC Safety Evaluation of BWRVIP-62

Reference:

1. Letter from Jack R. Strosnider (NRC) to Carl Terry (BWRVIP Chairman), "Safety Evaluation of Proprietary EPRI Report TR-108705, BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), (TAC NO. MA4468)," dated January 30, 2001.
2. Letter from Carl Terry (BWRVIP Chairman) to NRC Document Control Desk, "PROJECT NO. 704 – BWRVIP Response to NRC Safety Evaluation of BWRVIP-62," dated August 1, 2001.
3. Letter from Carl Terry (BWRVIP Chairman) to NRC Document Control Desk, "PROJECT NO. 704 – BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), EPRI Report TR-108705, December 1998," dated December 31, 1998.

Enclosed are 10 copies of the supplement to the BWRVIP response to the issues identified in the NRC Safety Evaluation (SE) of the BWRVIP report "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)" transmitted by the Reference 1 letter identified above. The initial BWRVIP response to the NRC SE on BWRVIP-62 was transmitted to the NRC by the Reference 2 letter identified above.

Please note that the enclosed document contains proprietary information. Therefore the request to withhold the BWRVIP-62 report from public disclosure transmitted to the NRC by the Reference 3 letter identified above also applies to the enclosed document.

CORPORATE HEADQUARTERS
3412 Hillview Avenue | Palo Alto CA 94304-1395 USA | 650.855.2000 | Customer Service 800.313.3774 | www.epri.com

If you have any questions on this subject, please contact John Wilson of Exelon (BWRVIP Mitigation Committee Technical Chairman) by telephone at 630.657.3200.

Sincerely,

Carl Terry
Constellation Generation Group
Nine Mile Point Nuclear Station
Chairman, BWR Vessel and Internals Project

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Supplement to the BWRVIP Response to Issues in NRC Safety Evaluation of "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), EPRI TR-108705,"

Background

The NRC issued a Safety Evaluation (SE) of the "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), EPRI TR-108705," on January 30, 2001. The SE identified several issues (open items) in the report and requested BWRVIP to address these items in a revised, final BWRVIP-62 report. BWRVIP issued a response (BWRVIP Document, 2001-250, August 1, 2001) to the NRC in which each open item was addressed. A follow up meeting between BWRVIP and NRC was held on October 29, 2001 at Argonne National Laboratory (ANL) to discuss the BWRVIP response to open items in the SE. At that meeting the NRC requested the following supplementary information:

- For NMCA plants, provide additional field ECP data to support that hydrogen to oxygen molar ratio of 2:1 (rather than 4:1) provides adequate protection. (Open Item 3.2.3)
- For Moderate HWC plants (Category 1) provide additional technical arguments to show that the radiolysis-ECP model provides a conservative prediction of ECP in non-monitored locations (Open Item 3.2.5)

BWRVIP prepared the supplementary information and presented it to the NRC at meeting on June 12-13, 2002 at ANL. NRC requested BWRVIP to provide the following additional information regarding Open Item 3.2.3:

- Provide hydrogen to oxygen molar ratio calculation by the BWRVIP radiolysis ECP model for Quad Cities 2, Susquehanna and a BWR-6 unit.
- Provide any additional plant data for ECP vs. feedwater hydrogen response for NMCA plants.

This document is a Supplement to BWRVIP Response (BWRVIP Document, 2001-250, August 1, 2001) to the NRC SE. Below are the open items identified by the NRC and the BWRVIP response to each item.

Open Item 3.2.3 Noble Metal Chemical Application/Additions (NMCA)

The staff requested additional data to justify a reduction in the staff's recommended minimum molar ratio from 4:1 and to provide additional data justifying Figures 1 and 2 in the BWRVIP response to Open Item 3.2.3.

Response to Open Item 3.2.3

Figure 1 includes ECP data from Duane Arnold upper core, lower core and recirculation, Peach Bottom 2 RWCU, Quad Cities 1 and 2 RWCU, Dresden 2 RWCU and Hatch 1 bottom head drain line. It confirms that the ECP drops to a value of [redacted] mV SHE between [redacted] [redacted] feedwater hydrogen irrespective of the plant type or the monitoring location.

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The plant ECP response is consistent with $H_2:O_2$ molar ratios calculated with the BWRVIA radiolysis model. These calculations show that the molar ratio changes from less than 2 to greater than 2 between Content Deleted - EPRI Proprietary Information ppm feedwater hydrogen at all locations between the top of the downcomer to the bottom of the vessel. For example, Figure 2 shows the hydrogen to oxygen molar ratio calculated by the BWRVIA radiolysis ECP model for Duane Arnold at various locations within the vessel. At feedwater hydrogen concentrations of ppm the molar ratios at all locations are less than [illegible] As the concentration is increased to ppm the molar ratios exceed 2 at all locations between the top of the downcomer to the bottom of the vessel. The ratio stays below two in locations above the core such as the mixing plenum. The molar ratios are highest in the recirculation and lower downcomer, intermediate in the lower plenum and lowest in the upper downcomer, which is the limiting location

The molar ratio results for Hatch 1 shown in Figure 3 are very similar to Duane Arnold. For both units the change in molar ratio from <2 to >2 that occurs at a feedwater hydrogen concentration between Content Deleted - EPRI Proprietary Information ppm which is consistent with the sharp drop in the measured ECP shown in Figure 1.

Figures 4, 5 and 6 show the molar ratio calculations for Kuosheng (a BWR-6), Susquehanna and Quad Cities 2. It should be noted that Kuosheng and Susquehanna are not using NMCA and these results are provided only for comparison. The molar ratio results for Kuosheng and Susquehanna are very similar to Hatch 1 and Duane Arnold in that both plants show a transition in molar ratio to >2 at a feedwater hydrogen concentration between Content Deleted - EPRI Proprietary Information ppm. On the other hand, this transition occurs at a higher concentration of Content Deleted - EPRI Proprietary Information ppm hydrogen for Quad Cities 2 even though the ECP measurements in Figure 1 indicate protection at a lower hydrogen concentration Content Deleted - EPRI Proprietary Information. The reason for this difference is not clear. However, the model prediction for Quad Cities 2 is conservative because ECP measurements clearly show that protection was achieved at a lower hydrogen concentration than predicted by the model.

In summary the plant ECP measurements confirm that the model is doing a good job of predicting the feedwater hydrogen concentration at which the molar ratios in various locations in the vessel will exceed 2 and will provide protection.

These results confirm that a molar ratio of 2 will provide mitigation in NMCA plants. Based on the information presented above BWRVIP concludes that a molar ratio target of three (3) should provide adequate margin for NMCA plants. This target molar ratio of 3 is applied to the measurement location, which is typically a reactor coolant sample location representative of recirculation loop conditions. This ensures that a conservative margin above the required 2:1 is maintained for all vessel internal locations and primary coolant target piping locations. The BWRVIP position is consistent with the GE RICSIL No. 087 where GE has recommended that NMCA plants should have a target of at least 3:1 hydrogen to oxidant molar ratio. The reason for the higher molar ratio is to provide adequate margin. If a plant is unable to maintain a molar ratio of 3:1 due to high radiation dose levels then a plant specific submittal may be made to demonstrate adequate mitigation at a lower molar ratio (between 2 and 3).

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~~**BWRVIP-62 Table 3-5 (Revised)**~~

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Figure 1: ECP vs. feedwater hydrogen response of NMCA treated BWRs

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Figure 2: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for Duane Arnold.

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(Bypass: Core bypass, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPB: Lower plenum bottom, LPT: Lower plenum top, MP: Mixing plenum)

Figure 3: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for Hatch 1.
(Bypass: Core bypass, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPB: Lower plenum bottom, LPT: Lower plenum top, MP: Mixing plenum)

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Figure 4: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for Kuosheng (BWR-6).
(Bypass: Core bypass, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPB: Lower plenum bottom, LPT: Lower plenum top, MP: Mixing plenum)

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Figure 5: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for Susquehanna.
(Bypass: Core bypass, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPB: Lower plenum bottom, LPT: Lower plenum top, MP: Mixing plenum)

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Figure 6: Hydrogen to oxygen molar ratio calculated by BWRVIA radiolysis ECP model for Quad Cities 2.
(Bypass: Core bypass, UDC: Upper downcomer, LDC: Lower downcomer, Recirc: Recirculation line, JP: Jet pump, LPB: Lower plenum bottom, LPT: Lower plenum top, MP: Mixing plenum)

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Open Item 3.2.5 Moderate HWC Plants (Category 1)

The staff requested additional technical arguments to show how a moderate HWC plant with ECP monitoring (Category 1) can assure protection of non-monitored locations in the vessel

Response to Open Item 3.2.5

BWRVIP believes that the approach proposed in the response to this open item in BWRVIP Document 2001-250, August 1, 2001 will provide adequate assurance of protection in non-monitored locations. This approach will be used for plants or locations where the ECP model is non-conservative compared to plant ECP measurements

The approach consists of deriving a correlation between the measured ECP and calculated total oxidant (O_2 ppb + ½ H_2O_2 ppb) as a function of feedwater hydrogen concentration at a particular location for a plant. The BWRVIA model will be used to calculate total oxidant. This correlation will be used to determine the total oxidant concentration at which the ECP decreases to –230 mV (SHE). If the total oxidant calculated at other locations in the vessel is less than the concentration that corresponds to an ECP of –230 mV (SHE), then effective mitigation should be assured at those locations. In summary, this approach uses the plant ECP data to calibrate the BWRVIA Radiolysis ECP model.

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SUPPLEMENTARY INFORMATION ON IMPLEMENTATION OF BWRVIP-62: DECEMBER 17, 2004

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BWRVIP BWR Vessel & Internals Project 2004-532

December 17, 2004

Document Control Desk
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Meena Khanna

Subject: Project No. 704 – Supplementary Information on Implementation of BWRVIP-62

References: Letter from Carl Terry (BWRVIP Chairman) to Document Control Desk (NRC), "Project No. 704 – BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), EPRI Report TR-108705, December 1998," dated December 31, 1998.

Enclosed are ten (10) copies of supplementary information on implementation of the document entitled "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62)." This supplementary information was requested by the NRC staff as a result of several discussions between the NRC staff and BWRVIP representatives.

Please note that the enclosed document contains proprietary information. Therefore, the request to withhold the BWRVIP-62 report from public disclosure transmitted to the NRC by the BWRVIP letter referenced above also applies to the enclosed document.

If you have any questions on this subject, please contact Jeff Goldstein (Entergy, BWRVIP Mitigation Committee Chairman) by telephone at 914.272.3512.

Sincerely,

William A Eaton

William A. Eaton
Entergy Operations
Chairman, BWR Vessel and Internals Project

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Supplementary Information on Implementation of BWRVIP-62 for Category 1, 2 and 3 Plants

The staff is in the process of preparing the final SE of "BWRVIP-62: Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection." The report is will be utilized by BWRVIP to develop and propose revised inspection intervals for BWR internals. The staff requested a meeting with BWRVIP prior to finalizing the SE. A meeting was held on August 24-25, 2004 at NRC during which BWRVIP provided an overview of the BWRVIP-62 report, the BWRVIA Radiolysis ECP model and examples of its application to BWRs and summarized the previous communications between BWRVIP and NRC on BWRVIP-62. Following the meeting the NRC requested BWRVIP to provide supplementary information on the following items related to BWRVIP-62:

1. Provide details of how BWRVIP-62 will be implemented for Category 1, 2 and 3 plants using the proposed primary and secondary parameters. Show how the proposed approach will address uncertainty in prediction of ECP by the BWRVIA model and ensure effective mitigation in non-monitored locations (i.e. locations without ECP probes) within the vessel and piping for each category.
2. Provide a physical explanation for the BWRVIA model prediction that the H2/O2 molar ratio becomes equal to 2 everywhere in the regions downstream of the feedwater spargers to the boiling regions of the core at a single hydrogen feed rate or FW H2 concentration. Also, clarify the differences between the molar ratio requirements in the Supplementary BWRVIP response (2003-149) of April 20, 2003 and the GE RICSIL referenced in the response.
3. Provide technical reasons to show that HWC or NMCA will continue to mitigate growth of deep cracks.

This note is a follow up to the BWRVIP-NRC meeting of August 24-25 and provides the information requested by the staff regarding implementation of BWRVIP-62

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1. Implementation of BWRVIP-62 for Category 1, 2 and 3 Plants

The primary and secondary parameters to be used by Category 1, 2 and 3 plants are listed in the revised Table 3-5 below:

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Category 1 Moderate HWC Plant: Primary Parameter

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Category 1 Moderate HWC Plant: Secondary Parameters

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BWRVIP stated in the August 1, 2001 response to the NRC SE of BWRVIP-62 (BWRVIP Letter 2001-250) that a minimum of two secondary parameters shall be used and that that the secondary parameters shall be validated once every ten years. However, if a plant implements a major power uprate (e.g. > 5%) then a revalidation of secondary parameter is necessary.

Category 1 Moderate HWC Plant: Application of BWRVIA Radiolysis ECP Model
It is not practical to use ECP probes at all locations in the vessel or piping. The plant

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Because of uncertainty in ECP predictions it is recommended that feedwater hydrogen should be high enough to satisfy both total oxidant and ECP criteria in non-monitored locations:

1. Total oxidant from BWRVIA model shall be equal to or less than [redacted]pb and
2. Low flow ECP from the BWRVIA model shall be less than [redacted] nV SHE

Category 2 Moderate HWC Plants (No ECP Probes)
The plants in Category 2 will have to make a plant specific submittal to show that they have an effective HWC program. These plants shall use the BWRVIA model to estimate the total oxidant and ECP at various locations as discussed in the previous section. If ECP vs. feedwater hydrogen measurements from a sister plant (e.g. Figures 1 and 2) are available then these shall be used to verify the model predictions. Similarly ECP vs. secondary parameter data from sister plants (e.g. Figure 3) shall also be used if available. The criteria for mitigation will be the same as those for Category 1 plants:

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1. Total oxidant from BWRVIA model shall be equal to or less than ppb and
2. Low flow ECP from the BWRVIA model shall be less than SHE

BWRs in this category shall provide additional margin by increasing the hydrogen injection rate because of lack of ECP data directly from the plant.

Category 3a NMCA Plants: Primary Parameters

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Category 3a NMCA Plants: Secondary Parameters

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Category 3a NMCA Plants: Application of BWRVIA Radiolysis ECP Model

It is not possible to locate ECP probes in all locations of interest in the vessel. The BWRVIA model shall be used to predict the molar ratio at various locations within the vessel and piping as a function of feedwater hydrogen as shown in Figures 7 and 8. The model prediction of feedwater hydrogen required for a molar ratio of two shall be compared and verified at the location of ECP measurement. A predicted molar ratio of two or more in the non-monitored locations will ensure effective NMCA and IGSCC mitigation.

Category 3b NMCA Plants: Primary Parameters

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Category 3b NMCA Plants: Secondary Parameters
During the hydrogen ramping test the plant shall correlate the measured molar ratio with a minimum of two secondary parameters listed in Table 3-5. These secondary parameters will be used to ensure effective NMCA if molar ratio measurements are not available

Category 3b NMCA Plants: Application of BWRVIA Radiolysis ECP Model
It is not possible to measure the molar ratio at all locations of interest in the vessel or piping. The BWRVIA model shall be used to predict the molar ratio at various locations within the vessel and piping as shown in Figures 7 and 8. The model prediction of feedwater hydrogen required for a molar ratio of two shall be compared and verified at the location of molar ratio measurement. A predicted molar ratio of two or more in the non-monitored locations will ensure effective NMCA and IGSCC mitigation.

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Table 1a
Implementation Steps for Category 1 and 2 (HWC-M) Plants

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Table 1b
Implementation Steps for Category 3a and 3b (NMCA) Plants

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Figure 1: Susquehanna 1 Lower Plenum ECP vs. Feedwater Hydrogen

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Figure 2: Garona Lower Plenum ECP vs. Feedwater Hydrogen

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Figure 3: Measured ECP near Bottom of Core Correlated with Normalized Main Steam Line Radiation Fields (From BWRVIP-62)

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Figure 4: Predicted Total Oxidant in Outer Bypass for Susquehanna 1

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Figure 5: Predicted Total Oxidant in the Lower Vessel Head Region for Susquehanna 1

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Figure 6: ECP vs. Feedwater Hydrogen Response of NMCA Treated BWRs

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Figure 7: Hydrogen to Oxygen Molar Ratio Calculated by BWRVIA Radiolysis ECP Model for Duane Arnold

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Figure 8: Hydrogen to Oxygen Molar Ratio Calculated by BWRVIA Radiolysis ECP Model for Hatch 1

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2.1 Physical Explanation of Molar Ratio Predictions of BWRVIA Model

This section provides a physical explanation for the BWRVIA model prediction that the H_2/O_2 molar ratio becomes equal to 2 everywhere in the regions downstream of the feedwater spargers to the boiling regions of the core at a single hydrogen feed rate or FW H2 concentration.

The basic chemical reactions for hydrogen and oxygen in the reactor are:

Radiolytic decomposition and recombination:

$8 H_2O \text{ <--> } 6 H_2 + 2 O_2 + 2 H_2O_2$

This reaction goes to an equilibrium depending on the concentrations of H2, O2 and H2O2. If H2 is added, the reaction shifts to the left, O2 and H2O2 are consumed, and we say "recombination" occurs. This reaction only occurs in the presence of a radiation field, and the rate of reaction is governed by the radiation flux and the concentrations of reactants.

Decomposition of H_2O_2

$2 H_2O_2 \text{ ---> } 2 H_2O + O_2$

This is a thermal decomposition reaction, independent of radiation flux. The peroxide "half-life" in reactor coolant is ~15 seconds. Decomposition also occurs on surfaces.

Corrosion reactions can consume O_2 and H_2O_2 (or produce H_2, in the absence of O_2 and H_2O_2). However, the rate of these reactions is very slow compared to the above reactions, and therefore they don't affect the concentration of H_2, O_2 and H_2O_2.

The above two reactions can be "summed" and simplified to:

$2 H_2O \text{ <--> } 2 H_2 + O_2$

Under normal water chemistry, there is a deficiency of hydrogen: the molar ratio of H_2/O_2 is <2. As hydrogen is added with feedwater, the molar ratio increases everywhere in the non-boiling regions downstream of the feedwater spargers. Once the ratio is raised to 2 at the feedwater spargers, it must be 2 everywhere else because the only chemical reaction that could change the ratio is the recombination reaction, $2 H_2 + O_2 \text{ ---> } 2 H_2O$. This ratio removes 2 moles of hydrogen for every mole of O_2 consumed. So, at the H_2 injection rate that gives a mole ratio of exactly 2 at the feedwater spargers, the mole ratio will remain exactly 2 everywhere downstream.

Now, if slightly more hydrogen were added, the molar ratio would become slightly higher than 2 at the feedwater spargers. However, as the water flowed into the region of radiation flux, recombination reactions would occur. Since hydrogen is in excess, oxygen would be consumed and the ratio would increase, going to infinity as the oxygen (in the denominator) went to zero while there was still some excess hydrogen.

This can also be shown mathematically as follows. Assume for NWC (prior to hydrogen addition), the initial concentrations of hydrogen, oxygen and the molar ratio are:

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$H_2 = H_2\text{-NWC}$

$O_2 = O_2\text{-NWC}$;

Molar ratio $H_2\text{-NWC}/O_2\text{-NWC} < 2$

After hydrogen addition assume:

H_2 Added = H_2-ADD

O_2 Consumed = X

Then H_2 Consumed = 2X

H_2/O_2 Ratio = $(H_2\text{-NWC} + H_2\text{-ADD} - 2X)/(O_2\text{-NWC} - X)$ (1)

At the feedwater spargers, X = 0 (no radiation flux, no consumption of hydrogen or oxygen)

Determine H_2-ADD for H_2/O_2 Ratio = 2 at the feedwater spargers

$2 = (H_2\text{-NWC} + H_2\text{-ADD})/O_2\text{-NWC}$

$H_2\text{-ADD} = 2\ O_2\text{-NWC} - H_2\text{-NWC}$

Substitute into general expression for molar ratio, Equation (1)

H_2/O_2 Ratio = $(H_2\text{-NWC} + 2\ O_2\text{-NWC} - H_2\text{-NWC} - 2X)/(O_2\text{-NWC} - X)$

H_2/O_2 Ratio = $2(O_2\text{-NWC} - X)/(O_2\text{-NWC} - X) = 2$

In other words, it doesn't matter what value of "X" is (i.e. how much oxygen has been consumed by recombination). The molar ratio remains "2" independent of where the water is.

Now, assume $H_2\text{-ADD} = 2\ O_2\text{NWC} - H_2\text{-NWC} + H_2\text{-EXCESS}$ (2)

Where H_2-EXCESS = the amount of H2 over that needed for a 2/1 ratio

Substituting for H_2-ADD in Equation 1

$H_2/O2_2$Ratio = $(H_2\text{-NWC} + 2\ O_2\text{-NWC} - H_2\text{-NWC} + H_2\text{-EXCESS} - 2X)/(O_2\text{-NWC} - X)$

H_2/O_2 Ratio = $(2\ O_2\text{-NWC} + H_2\text{-EXCESS} - 2X)/(O_2\text{-NWC} - X)$

$= (2\ O_2\text{-NWC} - 2X)/(O_2\text{-NWC} - X) + H_2\text{-EXCESS}/(O_2\text{-NWC} - X)$

$= 2 + H_2\text{-EXCESS}/(O_2\text{-NWC} - X)$

As "X" (the amount of oxygen consumed increases, the denominator of the "adder" term becomes smaller, the "adder" term increases, and the molar ratio goes >2.

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2.2 Molar Ratio Requirements in BWRVIP-62

The Supplementary BWRVIP response (2003-149) of April 20, 2003 (Page 2) states that: "These results confirm that a molar ratio of 2 will provide mitigation in NMCA plants. Based on the information presented above BWRVIP concludes that a molar ratio target of three (3) should provide adequate margin for NMCA plants. This target molar ratio of 3 is applied to the measurement location, which is typically a reactor coolant sample location representative of recirculation loop conditions. This ensures that a conservative margin above the required 2:1 is maintained for all vessel internal locations and primary coolant target piping locations. The BWRVIP position is consistent with the GE RICSIL No. 087 where GE has recommended that NMCA plants should have a target of at least 3:1 hydrogen to oxidant molar ratio. The reason for the higher molar ratio is to provide adequate margin. If a plant is unable to maintain a molar ratio of 3:1 due to high radiation dose levels then a plant specific submittal may be made to demonstrate adequate mitigation at a lower molar ratio (between 2 and 3)."

It should be clarified that the target molar ratio of 3 in the BWRVIP response applies to a molar ratio measurement made at a reactor coolant sample location whereas the molar ratio in the GE RICSIL No. 087 refers to a calculated value at a location to be protected. It is obvious from Figures 7 and 8 that the feedwater hydrogen concentrations required to achieve a molar ratio of 3 at these different locations will vary as shown in Figures 7 and 8.

3. Mitigation of Deep Cracks by HWC or NMCA

During the BWRVIP-NRC meeting on August 24-25, 2004 in Rockville, MD and a follow up conference call on September 29, 2004 the staff requested BWRVIP to provide technical reasons to show that HWC or NMCA will continue to mitigate growth of deep cracks. This note addresses the staff request.

Theoretical and experimental studies have been conducted to determine crack mouth and crack tip pH and potentials in stainless steels in BWR normal water chemistry (NWC) and hydrogen water chemistry (HWC) environments and their role in IGSCC (e.g. Peter Andresen, "Modeling of Water Chemistry and Material Chemistry Effect on Crack Tip Chemistry and Resulting Crack Growth Kinetics", Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, August 30-September 3, 1987, pp 301, Traverse City, Michigan).

These studies clearly show that in an oxidizing BWR environments:

- The potential at the crack tip is low typically ~ -600mV SHE
- The potential at the crack mouth is high ~ 0 to +100mV SHE
- Because of the potential gradient the pH at the crack tip becomes more acidic and more concentrated in anionic species such as chloride and sulfate which may be present in bulk water

The IGSCC process in NWC is driven by a combination of the aggressive crack tip environment, applied and residual stresses and a susceptible material.

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In HWC environment

- The potential at the crack tip is low
- The potential at the crack mouth is low
- In the absence of a potential gradient the pH at the crack tip stays near neutral and there is little concentration of anionic species

In HWC or NMCA environment the IGSCC process slows down because the crack tip environment is less aggressive than in an NWC environment.

Studies have also shown that localized crack tip chemistry can exist in cracks when they reach depths of 2 mil (50 microns) or more. Crack growth tests show that deep cracks respond to HWC in the same way as shallower cracks with depths of 2 mil or more. It is the potential difference between the crack tip and crack mouth that determines whether an aggressive environment will be created at the crack tip. HWC or NMCA mitigates IGSCC by eliminating or reducing the potential gradient between the crack mouth and crack tip which leads to a less aggressive environment at the crack tip irrespective of crack depth.

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NRC SAFETY EVALUATION OF BWRVIP-62: JULY 22, 2008

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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July 22, 2008

Mr. Rick Libra
Exelon
Chairman, BWR Vessel and Internals Project
Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94304-1395

SUBJECT: SAFETY EVALUATION FOR ELECTRIC POWER RESEARCH INSTITUTE (EPRI) BOILING WATER REACTOR (BWR) VESSEL AND INTERNALS PROJECT (BWRVIP) REPORT TR-108705 (BWRVIP-62) "BWRVIP-62: BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION" (TAC NO. MA4468)

Dear Mr. Libra:

By letter dated December 31, 1998, as supplemented by letters dated August 1, 2001, May 19, 2003, and December 17, 2004, the EPRI submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval BWRVIP report TR-108705 (BWRVIP-62), "BWRVIP-62: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection." The BWRVIP-62 report provides a systematic methodology for evaluating the effectiveness of hydrogen water chemistry and noble metal chemical application for the mitigation of intergranular stress corrosion cracking of reactor internals when direct measurements of the internals' corrosion potential are not feasible.

On January 30, 2001, the NRC staff issued its initial safety evaluation (SE) for BWRVIP-62. This SE contained open items which are described in more detail in Section 3.0 of the enclosed SE. In response to the open items contained in the NRC staff's SE of January 30, 2001, the BWRVIP provided technical information related to the implementation of the BWR Vessel Internals Application model in a letter dated August 1, 2001, followed by supplemental information in letters dated May 19, 2003, and December 17, 2004. The NRC staff reviewed BWRVIP-62 to determine whether this report provides an adequate technical basis for implementing modified inspection requirements for BWR reactor vessel internal components that are protected from intergranular stress corrosion cracking based on the methods described in BWRVIP-62.

The NRC staff has reviewed BWRVIP-62 and finds that this BWRVIP report is acceptable for referencing in licensing documentation for General Electric-designed BWRs to the extent specified and under the limitations delineated in the BWRVIP report and in the enclosed SE. The SE defines the basis for our acceptance of the BWRVIP-62.

Notice: Enclosure 2 transmitted herewith contains ~~proprietary information.~~
~~When separated from Enclosure 2, this document is decontrolled.~~

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Our acceptance applies only to material provided in the subject BWRVIP report. We do not intend to repeat our review of the acceptable material described in the BWRVIP report. When the BWRVIP report appears as a reference in licensing documentation, our review will ensure that the material presented applies to the specific plant involved. Licensees will be expected to implement the provisions of BWRVIP-62, subject to the limitations in the enclosed SE, as part of their BWRVIP program unless deviations from the program are justified. Licensees shall identify such deviations to the NRC staff in accordance with BWRVIP program requirements.

In accordance with the guidance provided on the NRC website, we request that the BWRVIP publish accepted proprietary and non-proprietary versions of this BWRVIP report within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC staff requests for additional information and the responses. The accepted versions shall include an "-A" (designating accepted) following the BWRVIP report identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this BWRVIP report, the BWRVIP and/or licensees referencing it will be expected to revise the BWRVIP report appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

Mark J. Max

Mark J. Maxin, Acting Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 704

Enclosures: 1. Non-proprietary SE
2. Proprietary SE

cc w/encl 1 only: See next page

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3/13/08

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION BOILING WATER REACTOR (BWR) VESSEL AND INTERNALS PROJECT (BWRVIP) REPORT TR-108705 (BWRVIP-62): "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR INSPECTION RELIEF FOR BWR INTERNAL COMPONENTS WITH HYDROGEN INJECTION"

BWRVIP

PROJECT NO. 704

1.0 INTRODUCTION

1.1 Background

By letter dated December 31, 1998 (Agencywide Documents Access and Management System (ADAMS) Accession No. 9901050050), as supplemented by letters dated August 1, 2001 (ADAMS Accession No. ML012140408), May 19, 2003 (ADAMS Accession No. ML031430145), and December 17, 2004 (ADAMS Accession No. ML043560323), the Electric Power Research Institute (EPRI) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval BWRVIP report TR-108705 (BWRVIP-62), "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection." A non-proprietary version of BWRVIP-62 was sent on March 7, 2000 and is available in ADAMS under Accession No. ML003691748. BWRVIP-62 contains a discussion of the technical basis for relief from current inspection requirements for BWR reactor vessel internal components (RVIs) that are protected from intergranular stress corrosion cracking (IGSCC) by the injection of hydrogen into the reactor coolant.

On January 30, 2001, the NRC staff issued its initial safety evaluation (SE) (ADAMS Accession No. ML010370141) for BWRVIP-62. This SE contained open items which are described in more detail in Section 3.0 of this SE. In response to the open items contained in the NRC staff's SE of January 30, 2001, the BWRVIP provided technical information related to the implementation of the BWR Vessel Internals Application (BWRVIA) model in a letter dated August 1, 2001, followed by supplemental information in letters dated May 19, 2003, and December 17, 2004. The NRC staff has reviewed the responses, and its comments and recommendations regarding these responses are stated in Section 3.0 of this SE.

1.2 Purpose

The NRC staff reviewed BWRVIP-62 to determine whether this report provides an adequate technical basis for implementing modified inspection requirements for BWR RVIs that are

~~Official Use Only – Proprietary Information~~ ENCLOSURE 2 protected from IGSCC based on the methods described in BWRVIP-62. This SE considered the role of neutron fluence on IGSCC, the rates of crack propagation, aspects of the physical chemistry, effects of electrochemical corrosion potential (ECP), coolant flow and noble metal chemical application (NMCA) on IGSCC susceptibility, the radiolysis and ECP models, and an assessment of the effectiveness of hydrogen injection.

1.3 Organization of the SE

Section 2.0 of this SE summarizes BWRVIP-62. Section 3.0 evaluates each topic in Section 2.0 of this SE. Section 3.0 also evaluates how the BWRVIP addressed the open items from the NRC staff's SE of January 30, 2001. Section 4.0 summarizes the conclusions resulting from this SE.

2.0 SUMMARY OF BWRVIP-62

BWRVIP-62 contains a discussion of the technical basis for implementing modified inspection requirements for BWR RVIs that are protected from IGSCC based on the methods described in BWRVIP-62 (involving the injection of hydrogen into the reactor coolant).

Section 1.0 of BWRVIP-62 describes the two primary techniques for protecting RVIs from IGSCC by means of hydrogen injection, or hydrogen water chemistry (HWC). The first of these techniques is moderate hydrogen water chemistry (HWC-M) whereby hydrogen is injected into the reactor coolant at rates higher than would typically be used to protect piping. The second of these techniques is NMCA whereby a continuous injection of a small amount of hydrogen is supplemented by an occasional batch injection of a small amount of noble metal compounds which act as catalysts for the recombination reactions. This section also presents a comprehensive survey of previous cracking events in BWR RVIs due to IGSCC and studies which indicate the effectiveness of HWC in mitigating IGSCC.

Section 2.0 of BWRVIP-62, describes radiolysis/ECP computer models used to determine the effectiveness of hydrogen injection techniques for mitigating IGSCC. The use of high purity water in BWRs for the neutron moderator and primary coolant coupled with water radiolysis due to neutron and gamma radiation, results in high ECP and increases the susceptibility of RVIs to IGSCC. The effectiveness of mitigation techniques can be assessed by directly measuring ECP (as measured by a standard hydrogen electrode) at a specific location of interest in the RVIs. However, direct ECP measurements at specific locations in the RVIs can be cumbersome due to the relative inaccessibility of some RVIs. Therefore, the technical basis described in BWRVIP-62 included supplementary techniques that do not depend on direct measurement of the ECP at specific locations in the RVIs.

The BWRVIP developed a computer model known as BWRVIP radiolysis/ECP analysis - BWRVIA, as a supplementary technique to calculate the ECP values of the reactor coolant system (RCS) at a specific component location in the RVIs. In addition, the calculated ECP values obtained from the BWRVIA model can be correlated with the measurements of other plant parameters (e.g., oxygen concentration, main steam line radiation levels, etc.). Figure 2-8 of BWRVIP-62 shows the comparison between model calculation and plant measured data including [**Content Deleted - EPRI Proprietary Information** ,]. The measurements agree reasonably well with calculated results considering the uncertainties in all involved variables. The BWRVIP proposes to use this BWRVIA model as a tool to monitor plant water chemistry and ECP data. The NRC staff did not review the BWRVIA model. The NRC staff did, however, evaluate the results of the application of the model, which were submitted in BWRVIP-62 and in the responses to requests for additional information (RAIs) in letters dated August 1, 2001, May 19, 2003, and December 17, 2004.

In Section 3.0 of BWRVIP-62, the current operating history is reviewed and correlated to the corresponding plant water chemistry. A conclusion is drawn that HWC-M is able to reduce crack initiation and crack growth. Methods are described using hydrogen injection and NMCA with hydrogen injection. All of the above are in combination with ECP measurements or calculations. The effect of HWC-M and NMCA on the Nitrogen-16 isotope radiation of the main steam line is discussed. The crack growth correlation developed in BWRVIP-14, "Evaluation of Crack Growth in BWR Stainless Steel Reactor Vessel Internals" (Reference 1), is used to develop expected factors of reduction in crack growth rate corresponding to the expected reduction in ECP.

Section 4.0 discusses current inservice inspection (ISI) requirements and concludes implementation of either HWC-M or NMCA would result in lower IGSCC propagation rates which would justify inspection relief. With respect to the crack growth model and radiolysis results, an inspection program for the RVIs can be developed based on factors of improvement (FOI) for plants that have implemented either HWC-M or NMCA. The FOI calculated for each RVI, based on modeling results, would be applied to revise the inspection interval established in the various BWRVIP inspection and flaw evaluation (I&E) reports. The BWRVIP will propose and request NRC staff approval of revised inspection intervals for the RVIs for plants that have implemented either HWC-M or NMCA.

3.0 EVALUATION

BWR austenitic stainless steel and nickel-based alloy RVIs have experienced IGSCC, leading to degradation and potential safety concerns. Therefore, the NRC staff found it necessary for BWR licensees to perform regular inspections of RVIs to provide adequate assurance of their structural integrity. The BWRVIP developed several I&E guidelines for several safety-related RVIs which were reviewed and found acceptable by the NRC staff. However, due to the difficulty and expense of these RVI inspections, licensees find it desirable to demonstrate that fewer inspections are necessary when suitable IGSCC mitigation steps are taken.

Two primary techniques have been used to ensure mitigation of IGSCC in BWR RVIs using HWC. The first technique involves utilizing higher hydrogen injection rates than would typically be used to protect recirculation piping [Content Deleted - EPRI Proprietary Information)]. This technique is referred to as HWC-M and its goal is to provide sufficient additional hydrogen in order to lower ECP to protective levels in the lower plenum. The second protective technique is NMCA which involves a continuous injection of a small amount of hydrogen (to give a minimum threshold value of hydrogen-to-oxygen molar ratio in the single phase liquid region) supplemented by an occasional batch injection of catalytic noble metal compounds. Since both processes can protect RVIs from environmentally-assisted cracking degradation, the effective implementation of either HWC-M or NMCA at a BWR is considered an adequate basis for the implementation of a modified inspection program for RVIs.

With respect to the crack growth model and radiolysis results, an inspection program for the RVIs can be developed based on FOIs for plants that have implemented either HWC-M or NMCA. The FOI calculated for each RVI, based on modeling results, would be applied to revise the inspection interval established in the various BWRVIP I&E guidelines. The BWRVIP will propose revised inspection intervals for the RVIs for plants that have implemented either HWC-M or NMCA.

In its initial SE for BWRVIP-62 issued by letter dated January 30, 2001, the NRC staff found that the guidance provided in BWRVIP-62 is acceptable, pending the resolution of certain open items. In this SE, the NRC staff evaluates the BWRVIP response to each of these open items.

3.1 Technical Basis for HWC-M and NMCA

Section 1.0 of BWRVIP-62 provides a description of HWC techniques for mitigating IGSCC and presents evidence for the effectiveness of these techniques. The effectiveness of the HWC-M and NMCA is monitored by measuring the Content Deleted - EPRI Proprietary Information], the primary parameter in assessing the availability of hydrogen and/or noble metal compounds in the water surrounding RVIs. A protection potential of Content Deleted - EPRI Proprietary] or below in the RCS water can be achieved by the addition of hydrogen to the feedwater or the addition of hydrogen with noble metal compounds to the RCS water. For plants implementing NMCA, noble metals, such as platinum, palladium, or rhodium, can be used as a catalyst for the recombination of hydrogen with oxygen. Consequently, the hydrogen concentration required for plants implementing NMCA will be substantially lower than that required for plants implementing HWC-M.

BWRVIP-62 also provides technical requirements for maintaining the conductivity of the RCS water at a specific threshold level so that the susceptibility of the RVIs to IGSCC is minimized. The conductivity of RCS water is affected by the presence of ionic impurities which increases the susceptibility of RVIs to IGSCC. The NRC staff has reviewed and accepted the approach taken to control the conductivity of the RCS water below a threshold level.

In its initial SE dated January 30, 2001, the NRC staff issued five open items relevant to Section 1.0 of BWRVIP-62. The five open items (grouped into four areas) previously identified were: the effect of flow rate on the RCS water ECP, the role of neutron fluence and the effect of radiation on crack growth rates, the effect of radiation on ECP, and the assessment of HWC-M effectiveness with changing radiation levels. In addition, the NRC staff evaluated an issue not previously identified as an open issue: the effectiveness of HWC-M and NMCA in deep cracks. The NRC staff's evaluation of the BWRVIP responses to the five open items and the newly identified issue, are discussed below.

3.1.1 Effect of Flow Rate on ECP and Susceptibility of RVIs to IGSCC

This open item was identified as Open Item 3.2.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Under BWR normal water chemistry (NWC) conditions, the oxidation and reduction reactions on passive steel surfaces are limited by the mass transport of oxygen to the surface for the oxygen reduction reaction. Mass transport increases as flow increases and, thus, ECP is expected to increase with flow velocity.

By letter dated March 15, 2001, the BWRVIP submitted report TR-112314 "BWR Vessel and Internals Project, Effect of Flow Rate on Intergranular Stress Corrosion Cracking and Electrochemical Corrosion Potential," (BWRVIP-64) (ADAMS Accession No. ML010780076) for information only in response to the NRC staff's request. BWRVIP-64 discusses crack tip chemistry and the effect of flow rate on crack growth kinetics. The NRC staff did not formally review BWRVIP-64. However, the NRC staff did review Section 1.4 of BWRVIP-62, which provides data on the effect of flow rate on ECP values and crack growth rates, Figures 1-4 and 1-5, which were developed based on the detailed information provided in BWRVIP-64. The NRC staff agrees that crack growth rates remain low at higher flow rates because at higher flow rates the impurities and aggressive ions are flushed out of the crack tip region. Subsequently, the chemical concentration gradient between the tip of the crack and the bulk solution is reduced, resulting in the reduction of crack growth rates. The NRC staff concludes that the explanation provided in BWRVIP-62 regarding the effect of flow rate on the ECP and crack growth rates is a reasonable explanation to support the laboratory results and therefore, the NRC staff considers this open item closed.

3.1.2 Effectiveness of HWC-M and NMCA in Deep Cracks

This issue was not identified in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. However, by letter dated December 17, 2004, the BWRVIP issued a supplementary response in which it discussed the effectiveness of HWC-M and NMCA in deep cracks (crack depths equal to or greater than Content Deleted - EPRI Proprietary Information Theoretical and experimental studies have been conducted to determine crack mouth and crack tip pH and ECP and their role in IGSCC for stainless steels in HWC-M and NWC environments. The results of these studies are discussed in "Modeling of Water and Material Chemistry Effects on Crack Tip Chemistry and Resulting Crack Growth Kinetics" by Peter Andresen (Reference 2) which has been submitted to the NRC staff for information only. In cracks, the ECP gradient between the crack mouth and crack tip causes the pH at the crack tip to become more acidic and more concentrated in anionic species such as chlorides and sulfates which may be present in bulk water. The IGSCC process in NWC is driven by a combination of an aggressive crack tip environment, applied and residual stresses, and a susceptible material. In an HWC-M or NMCA environment, the ECP is low at both the crack tip and the crack mouth. Therefore, there is no ECP gradient and in the absence of a potential gradient, the pH at the crack tip stays near neutral and there is little concentration of anionic species. In an HWC-M or NMCA environment, the IGSCC process slows down because the crack tip environment is less aggressive. Studies have also shown that localized crack tip chemistry can exist in cracks when they reach depths of [Content Deleted - EPRI Proprietary Information] or more. However, in an HWC-M environment, crack growth tests show that deep cracks respond in the same way as shallower cracks.

Based on the information submitted for its review, the NRC staff concludes that plant operators can claim credit for an effective HWC-M environment when they: (1) maintain an established hydrogen concentration at the crack location for at least [Content Deleted - EPRI Proprietary Information] of the time that the plant is at power operation or hot standby conditions and (2) maintain the ECP value of RCS water at [Content Deleted - EPRI Proprietary Information] or below. Since the hydrogen concentration at plants implementing NMCA is lower than that at plants implementing HWC-M, the NRC staff concludes that plants implementing NMCA should maintain an established hydrogen concentration at the crack location for at least [Content Deleted - EPRI Proprietary Information] of the time that the plant is at power operation or hot standby conditions (i.e., a [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information] more time than that required at plants implementing HWC-M) in order to achieve the same protection against IGSCC in deep cracks. The NRC staff concludes that the ECP value of RCS water at the location of the crack should be maintained at [Content Deleted - EPRI Proprietary Information] or below to achieve protection from IGSCC.

The NRC staff understands that licensees follow the inspection guidelines that are provided in the relevant BWRVIP reports associated with each component and monitor the growth rates of deep cracks to verify that adequate protection is achieved with an effective HWC-M or NMCA environment. The NRC staff requests that the BWRVIP revise BWRVIP-62 to include the information provided in the BWRVIP letter dated December 17, 2004, which describes the effect of an HWC-M or NMCA environment on the crack growth rates of deep cracks. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated December 17, 2004.

3.1.3 Role of Neutron Fluence and the Effect of Radiation on Crack Growth Rates

This issue was identified as Open Items 3.1.1 and 3.1.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. This discussion focuses on crack growth rates due to irradiation assisted stress corrosion cracking (IASCC) in RVIs with an exposure to neutron fluences up to [Content Deleted - EPRI Proprietary Information] n/cm^2 (i.e., E > 1 MeV). When BWRVIP-62 was originally submitted, no data was available regarding crack growth rates in welds that are exposed to a neutron fluence value of [Content Deleted - EPRI Proprietary Information] n/cm^2 and above. Therefore, BWRVIP-62 evaluates taking credit for HWC and/or NMCA in welds that are exposed to neutron fluences less than [Content Deleted - EPRI Proprietary Information] n/cm^2. To provide a technical basis for evaluating the effectiveness of HWC and/or NMCA in welds with exposure to neutron fluences equal to or greater than [Content Deleted - EPRI Proprietary Information] n/cm^2, the BWRVIP, by letter dated December 20, 2001, submitted for NRC staff review and approval report 10030318, "Crack Growth Rates in Irradiated Stainless Steels in BWR Internal Components" (BWRVIP-99) (ADAMS Accession No. ML020020313). BWRVIP-99 provides technical requirements for determining crack growth rates for welds exposed to neutron fluences equal to or greater than [Content Deleted - EPRI Proprietary Information] n/cm^2. The NRC staff, in an SE sent by letter dated July 29, 2005, approved BWRVIP-99 (ADAMS Accession No. ML052150325). BWRVIP-99 can be used for evaluating crack growth rates in welds with exposure to neutron fluences equal to or greater than [Content Deleted - EPRI Proprietary Information] n/cm^2 provided they comply with all the conditions specified in the NRC staff's SE for this report. The NRC staff requests that BWRVIP-62 be revised to state that the crack growth rates specified in BWRVIP-99 shall be used for evaluating welds that are exposed to neutron fluences equal to or greater than [Content Deleted - EPRI Proprietary Information] n/cm^2. Based on this evaluation, the NRC staff considers this issue closed.

3.1.4 Effect of Radiation on ECP

This issue was identified as Open Item 3.2.1 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Previous research work has shown that IGSCC susceptibility and crack growth rates depend on the ECP of stainless steels in BWR environments. The ECP threshold limit for IGSCC is a function of the following: radiation exposure, concentrations of impurities in the coolant, and the microstructure and composition of the steel. BWRVIP-62 states that the ECP threshold limit for IGSCC initiation in irradiated Type 304 stainless steel may be as high as [Content Deleted - EPRI Proprietary Information]. Since there is a limited amount of data to support this value, the NRC staff requested that the BWRVIP retain the more conservative ECP threshold limit of [Content Deleted - EPRI Proprietary Information] for the irradiated stainless steel materials. In its response dated August 1, 2001, the BWRVIP concurred with the NRC staff and agreed to use a ECP threshold limit of [Content Deleted - EPRI Proprietary Information]. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP response letter dated August 1, 2001.

3.1.5 Assessment of HWC-M Effectiveness with Change in Radiation Levels

This issue was identified as Open Item 3.2.6 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. Previous work suggests that all radiolysis analyses have shown that radiation levels in the downcomer region have a strong effect on the rate of the hydrogen-oxygen recombination reaction. Since the radiation level in the downcomer varies throughout core life, the actual degree of mitigation due to HWC-M and/or NMCA will also vary. In its response by letter dated August 1, 2001, the BWRVIP stated that the radiolysis/ECP model (i.e., the BWRVIA model) will be used for both the beginning and end of life of a fuel cycle. The end of the fuel cycle should represent the most conservative case (i.e., there should be an increase in ECP at the end of the cycle). The NRC staff agrees with the proposal for using the BWRVIA model to calculate the total oxidant content at both the beginning and end of life of a fuel cycle, with the end of fuel cycle case being the most conservative. The BWRVIA model (discussed in Section 3.2 of this SE) takes into consideration the effect of radiation on the hydrogen-oxygen recombination reaction. These calculations should take into consideration the uncertainties that are associated with the application of the model and the additional conservative margin needed to compensate for any depletion of HWC-M at the downcomer region. The NRC staff requests that BWRVIP-62 be revised to include the information provided in the BWRVIP response to Open Item 3.2.6 sent by letter dated August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001.

3.2 Radiolysis and ECP models

Section 2.0 of BWRVIP-62 describes radiolysis/ECP computer models used to determine the effectiveness of hydrogen injection techniques for mitigating IGSCC. Section 2.0 of BWRVIP-62 also describes the basic concepts used in the application of the mathematical BWRVIA model used to establish the effectiveness of HWC-M/NMCA. The BWRVIA model will be used to determine chemistry conditions and the ECP at various locations in the RVIs measured as a function of feedwater hydrogen injection rate. The BWRVIA model will be benchmarked against the ECP measurement made at the plant of interest or at other plants, known as "sister plants," that are radiolytically identical and have similar operational characteristics. Previous results have indicated that plants of identical design and operation respond in a similar manner to the hydrogen injection rate. The BWRVIP defines sister plants as any pair or group of BWRs that are demonstrated to be radiolytically equivalent by a validated and benchmarked radiolysis model. Ordinarily, the effectiveness of the model can be ascertained by the measurement of the ECP of the RCS water at the location of interest in the RVIs. However, the measurement of ECP at remote locations in the RVIs is very cumbersome and not practical. Therefore, the BWRVIP proposes using the BWRVIA model to calculate the ECP value and total oxidant content of the RCS water at the location of interest.

Section 2.0 of BWRVIP-62 discusses the application of the BWRVIA model to calculate the two secondary parameters [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information] used to ensure the availability of HWC-M at the subject location. For the NMCA plants, the secondary parameters will include [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information]. BWRVIP-62 states that if a good correlation is established between the calculated ECP value and the secondary parameters, then the secondary parameters can be used to assess the availability of hydrogen and/or NMCA at the desired location. A minimum of two secondary parameters, preferably [Content Deleted – EPRI Proprietary Information Content Deleted - EPRI Proprietary Information] for HWC-M plants needs to be monitored. Additional secondary parameters for NMCA plants will include the measured value of [Content Deleted - EPRI Proprietary Information]. The secondary parameter data will be collected, maintained, and correlated to supplement the ECP probe data.

The BWRVIA model calculations include several parameters (e.g., mass flow, reactor power, feedwater hydrogen, oxygen). The BWRVIP also submitted data related to the application of the BWRVIA model in establishing correlation between the following parameters:

[Content Deleted - EPRI Proprietary Information]

[Content Deleted - EPRI Proprietary Information];

[Content Deleted - EPRI Proprietary Information].

The NRC staff did not review the BWRVIA model, but it evaluated the results of the application of the model, and finds that there is good agreement between the calculated and measured ECP values (at a few locations in some of the BWR RVIs). The NRC staff finds that Section 2.0 of BWRVIP-62 adequately provides the basic concepts used in the BWRVIA model which is used to calculate the ECP values of the RCS water at remote locations in the RVIs (i.e., where ECP values can not be measured easily). The NRC staff, in its initial SE dated January 30, 2001, requested that the BWRVIP discuss the validity of the BWRVIA model and the BWRVIP responses to NRC staff issues are discussed below.

The radiolysis model was discussed in Open Item 3.2.4 which was identified in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. For the past 10 years, the radiolysis model has undergone many changes. These changes include a refinement of the description of the primary system and the dose rate modeling of the ex-core regions and an updating of the neutron/gamma dose rates (the G values). The NRC staff requested that the BWRVIP provide a discussion of the significant differences between G values used in BWRVIP-62 and the G values used in similar approaches in Taiwan and Japan for analyzing the impact of HWC (References 3 and 4). The NRC staff also requested that results from a broader range of plants be included in a revised BWRVIP-62 in order to validate the capability of the model to predict water chemistries. Although numerous correlations of in-plant measurements are given in Figures 3-1 to 3-11 of BWRVIP-62, comparative model results in the referenced Appendix A of the BWRVIP-13 report, "Modeling Hydrogen Water Chemistry for BWR Applications" (Reference 5) are not presented in terms of the proposed secondary parameters. Because of this difference in presentation, it is not possible to determine whether the model results are representative of the range of behavior observed in the reactor vessel.

In its supplementary response sent by letter dated August 1, 2001, the BWRVIP stated that the G values, reaction rate constants, and some of the radiolysis schemes in the BWRVIA model were based on state-of-the-art techniques/information from the late 1980s. At that time, the integrated set of constants gave the best correlation with plant measurements. It was recognized that model inputs would have a range of uncertainties that would in turn result in uncertainties in the predictions. The approach used to address these uncertainties was to compare the model predictions of hydrogen, oxygen, and ECP obtained from specific locations to in-plant measurements of these same parameters obtained from the same locations.

The calculated and measured hydrogen and oxygen data obtained from the recirculation system of four plants, and the comparison of measured to calculated steam hydrogen and steam oxygen data presented in BWRVIP-62, indicate a close agreement between the measured and predicted hydrogen values in the reactor water. ECP values calculated by the model were compared with plant ECP measurements obtained at mid-core, core plate, recirculation flange and bottom head drain line locations. The measured data included [Content Deleted – EPRI Proprietary Information]

Content Deleted – EPRI Proprietary Information] that were installed at the aforementioned locations. The current BWRVIA model shows good agreement with plant chemistry data, as well as with plant ECP data obtained at specific locations in a limited number of plants. However, the data that was obtained from the [Content Deleted – EPRI Proprietary Information] plants show inconsistencies between the calculated and measured ECP values at the lower head region. The BWRVIP did not provide any explanation for this inconsistency. The BWRVIP, however, acknowledges that the model inputs have a range of uncertainties that would in turn result in uncertainties in predictions. The BWRVIP is planning to refine the model and reduce uncertainties in the model predictions, particularly in the lower head region. The BWRVIP proposes to submit its review of the BWRVIA models discussed in References 3 and 4 of this SE, along with additional research data on the ECP model related to the lower head region. The NRC staff will review these items when they are submitted for review.

As stated above, there are inconsistencies between the calculated and measured ECP values for RVIs obtained from the lower head region. Therefore, the NRC staff concludes that the BWRVIA model requires validation which can be achieved by installing an ECP probe specifically in this region. That is, if credit is desired for HWC and/or NMCA protection for lower head region components, an ECP measurement must be made in the lower head region volume. HWC credit can be claimed for RVIs in the lower head region provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value.

The NRC staff requests that the BWRVIP update BWRVIP-62 to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.4 sent by letter August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP response dated August 1, 2001.

3.3 HWC Effectiveness Assessment

In Section 3.0 of BWRVIP-62, the BWRVIP discusses the methodology for assessing the effectiveness of the use of HWC-M and NMCA in RCS water which is essential in mitigating IGSCC in RVIs. The BWR plants are categorized based on the verification methodology used for assessing the availability of HWC-M and/or NMCA. The categorization of the BWR plants and their characteristics are shown in Table 3.1 of this SE.

Category 1 plants use hydrogen to reduce the oxygen in the RCS water, and the hydrogen availability is assessed by measuring the [Content Deleted – EPRI Proprietary Information] at the location of interest. These plants will use this [Content Deleted – EPRI Proprietary Information] as a primary parameter for ensuring the effectiveness of HWC-M at that location. In addition, the BWRVIP proposes to implement continuous monitoring of two secondary parameters (e.g., [Content Deleted – EPRI Proprietary Information]) to ensure the availability of HWC-M at the subject location. Details regarding the verification methodology for assessing the availability of HWC-M in Category 1 plants are discussed in Section 3.3.3.1 of this SE.

Category 2 plants use hydrogen to reduce the oxygen in the RCS water, and the hydrogen availability is assessed by calculating the [Content Deleted – EPRI Proprietary Information] at the location of interest by using the BWRVIA model. Details regarding the verification methodology for assessing the availability of HWC-M in Category 2 plants are discussed in Section 3.3.3.2 of this SE.

Plants implementing NMCA additions have two categories, Category 3a and Category 3b. Category 3a plants use [Content Deleted – EPRI Proprietary Information] as primary parameters followed by continuous monitoring of two secondary parameters (e.g., [Content Deleted – EPRI Proprietary Information]) to ensure the availability of NMCA at the subject location. Category 3b plants use [Content Deleted – EPRI Proprietary Information] as primary parameters followed by continuous monitoring of two secondary parameters (e.g., [Content Deleted – EPRI Proprietary Information Content Deleted – EPRI Proprietary Information]) to ensure the availability of NMCA at the subject location. No ECP measurements are taken in Category 3b plants. Details regarding the verification methodology used to assess the availability of NMCA in Category 3a and Category 3b plants are discussed in Section 3.3.3.3 and 3.3.3.4 of this SE respectively.

3.3.1 Physical Chemistry Aspects of the HWC and/or NMCA Program

This issue was identified as Open Item 3.2 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. In its response sent by letter dated August 1, 2001, the BWRVIP proposed to incorporate changes to BWRVIP-62 regarding the following topics: (1) correlation of ECP measurements with the secondary parameters, (2) conductivity transients, (3) definition of an effective HWC-M, and (4) definition of an effective NMCA program. The NRC staff's evaluation of these topics is discussed below.

3.3.1.1 ECP Measurements

The BWRVIP proposes to use two reference electrodes to [Content Deleted – EPRI Proprietary Information] as a primary parameter for Category 1 plants. The BWRVIP letter of August 1, 2001, indicates that the [Content Deleted – EPRI Proprietary Information] for Category 1 plants will be correlated with secondary parameters, preferably [Content Deleted – EPRI Proprietary Information]. The NRC staff finds that the method of using the correlated secondary parameters to assess the effectiveness of HWC-M when the ECP probes fail is acceptable. The NRC staff concludes that maintaining a good correlation between ECP measurements and the secondary parameters is essential in monitoring effective HWC-M in RVIs. Additional methods using validated BWRVIA models or sister plant data are acceptable to verify the effectiveness of HWC-M if these methods are used in conjunction with secondary parameters. It is the NRC staff's conclusion that in the absence of ECP measurements (i.e., failure of the ECP probe), reliable and continuous monitoring of secondary parameters is essential to ensure that an effective level of protection is being maintained at the location of interest in the RVIs. The NRC staff understands that the reliability and accuracy of the secondary parameters can be maintained if these parameters are validated with in-situ measurements of the ECP. The BWRVIP intends to validate the secondary parameters using an [Content Deleted – EPRI Proprietary Information]. The NRC staff accepts this approach because it has previously accepted this method in its evaluation of Open Item 3.8 contained in its SE sent by letter dated September 15, 2000 (Reference 6) for BWRVIP report TR-113932, "BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)" (Reference 7).

To ensure adequate margin, the BWRVIP proposes to use a higher [Content Deleted – EPRI Proprietary Information Content Deleted – EPRI Proprietary Information] for the NMCA plants [Content Deleted – EPRI Proprietary Information]. BWRVIP-62, as supplemented by the BWRVIP responses, provides data that support the aforementioned position. The NRC staff reviewed the BWRVIP data and concludes that adequate mitigation of

IGSCC in the RVIs is achieved when the [Content Deleted – EPRI Proprietary Information] is maintained when measured at a recirculation loop location for NMCA plants. This value is consistent with the value recommended by [Content Deleted – EPRI Proprietary Information]. NMCA plants will implement a monitoring program that measures two secondary parameters to evaluate the adequacy of NMCA additions. The data submitted indicates that a good correlation is achieved between the measured ECP values and the secondary parameters.

Therefore, the NRC staff concludes that Category 3a plants (i.e., plants that implement NMCA and use [Content Deleted – EPRI Proprietary Information] as a primary parameter) maintaining a [Content Deleted – EPRI Proprietary Information Content Deleted – EPRI Proprietary Information] (measured at a location in a recirculation loop) will adequately mitigate IGSCC in RVIs. The BWRVIP states that if a plant is unable to maintain a [Content Deleted – EPRI Proprietary Information Content Deleted – EPRI Proprietary Information] due to high radiation dose levels, a plant-specific analysis can be performed to demonstrate adequate mitigation at a lower [Content Deleted – EPRI Proprietary Information]. However, NRC staff approval is required when intending to take plant-specific credit for an effective NMCA program when a [Content Deleted – EPRI Proprietary Information].

3.3.1.2 Conductivity Transients

The BWRVIP response issue, sent by letter dated August 1, 2001, indicates that when the reactor water conductivity exceeds the limits specified in BWRVIP report TR-103515-R2 "BWR Water Chemistry Guidelines – 2000 edition" (BWRVIP-79) (ADAMS Accession No. ML003722483), sent by letter dated June 2, 2000, for more than [[illegible]] hours, only the time in excess of [[illegible]] hours should be subtracted from the acceptable HWC-M available time. The NRC staff accepts this response because it has previously accepted this method in its SE (Open Item 3.8) for the BWRVIP-75 report (References 6 and 7). The BWRVIP recommends that contributions due to soluble iron may be subtracted from the measured conductivity for plants starting up with NMCA. The NRC staff accepts this response because the soluble iron in RCS water does not participate in the corrosion process, and the soluble iron does not affect the crack growth rate in RVIs.

3.3.1.3 Effective HWC-M Program

BWRVIP-62, as supplemented by the BWRVIP responses, provides data which indicate that a reduction in crack growth rates in RVIs can be achieved by controlling and monitoring HWC-M availability and by maintaining the reactor water ECP at a value equal to or less than [Content Deleted – EPRI Proprietary]. The BWR Owner's Group (BWROG) conducted in-plant measurements of ECP in 21 BWRs that are operating with HWC-M. This discussion summarizes the results associated with the effectiveness of HWC-M in recirculation system piping. The BWRVIP presented data which demonstrated that the ECP value obtained for a given feedwater hydrogen injection rate varied with component location. The BWRVIP stated that mitigation of IGSCC can be achieved when hydrogen is available for at least [Content Deleted – EPRI Proprietary] of the time that the plant is at power operation or hot standby conditions at an ECP value of [Content Deleted – EPRI Proprietary] or below. Based on the review of the data, the NRC staff agrees with this conclusion. The BWRVIP response states that when hydrogen injection is interrupted, no credit should be given for this time when calculating HWC-M availability. The interrupted time, in its entirety, should be counted as time that HWC-M is unavailable. The NRC staff concurs with this approach because it ensures that the calculation of the crack growth rate is based on a conservative calculation of the availability of HWC-M.

3.3.1.4 Effective NMCA Program

The BWRVIP in its response sent by letter dated August 1, 2001, states that effective NMCA is obtained for the plants when hydrogen is available for at least [Content Deleted – EPRI Proprietary] of the time that the plant is at power operation or hot standby conditions at an ECP value of [Content Deleted – EPRI] or below for the reactor water. In addition, the BWRVIP reiterates that a reduction in crack growth rate in the RVIs can be achieved by controlling and monitoring the hydrogen availability and NMCA addition and by maintaining the reactor water ECP at a value equal to or less than [Content Deleted – EPRI Proprietary]. BWRVIP-62, as supplemented by BWRVIP responses, provides adequate data to substantiate this claim. The NRC staff reviewed the submitted data and concludes that adequate mitigation of IGSCC in the RVIs of a NMCA plant is achieved when the measured secondary parameters correlate to the measured reactor water ECP of [Content Deleted – EPRI Proprietary] or below.

The NRC staff requests that the BWRVIP revise BWRVIP-62 to address the information stated in the BWRVIP response to Open Item 3.2 sent by letter dated August 1, 2001. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001.

3.3.2 Noble Metal Chemical Application/Additions

This issue was identified as Open Item 3.2.3 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. In its response sent by letter dated August 1, 2001, and supplemented by letter dated May 19, 2003, the BWRVIP addressed the issue related to hydrogen-to-oxygen molar ratio (Open Item 3.2.3) in NMCA plants. Details of this Open Item and the NRC staff's evaluation are discussed in Section 3.3.1.1 of this SE. As noted in Section 3.3.1.1, the NRC staff found the BWRVIP response acceptable.

3.3.3 ECP Model

This issue was identified as Open Item 3.2.5 in the initial NRC staff SE for BWRVIP-62 issued by letter dated January 30, 2001. The BWRVIA model in BWRVIP-62 is an empirical correlation relating concentrations of H_2, O_2, H_2O_2, and flow velocity to ECP. The results from six plants indicate that individual plant data appears to cluster either above or below the trend line, indicating that ECP cannot be simply estimated on the basis of the standard deviation based on the whole population of data. However, when grouped by plant, the data do not appear to be randomly distributed about the mean trend line. The NRC staff requested that the BWRVIP address the accuracy of the ECP measurements and the discrepancies between multiple ECP measurements. The ECP models applicable to the three categories of plants are addressed in Sections 3.3.3.1 (Category 1), 3.3.3.2 (Category 2), 3.3.3.3 (Category 3a), and 3.3.3.4 (Category 3b) of this SE.

In its response sent by letter dated August 1, 2001, supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that multiple probes of different types are used to measure the ECP and that the highest ECP value is used to assess the HWC-M effectiveness. The NRC staff agrees with this method because the most conservative ECP value is used to assess the HWC-M effectiveness.

For plants with HWC-M, the BWRVIP proposed to use the [Content Deleted – EPRI Proprietary Information] value as a primary parameter and use two continuously monitored secondary parameters (i.e., [Content Deleted – EPRI Proprietary Information]) to ensure the availability of HWC-M at the subject location. The BWRVIP stated that a good correlation will be established between the [Content Deleted – EPRI Proprietary Information] value and the secondary parameters so that, in the event of any failure of an ECP probe, the secondary parameters will be used to assess the hydrogen availability at the desired location. The plant will use the ECP data from the ramping test to select the hydrogen injection rate needed to ensure that the ECP value is maintained at or below [Content Deleted – EPRI Proprietary] at that location. The NRC staff agrees with this approach because this method ensures adequate HWC-M availability at the desired location when the secondary parameter values are maintained at or below the required threshold levels that correlate to an ECP value of [Content Deleted – EPRI Proprietary]. The BWRVIP also proposed to use the BWRVIA model to calculate the total oxidant at the area of interest as a function of feedwater hydrogen concentration. Based on the existing data, the BWRVIP claims that effective HWC-M availability is achieved when the total oxidant content at the area of interest is [Content Deleted – EPRI Proprietary Information] or less.

The BWRVIP presented data regarding the effect of RCS flow rates on crack growth rates and concluded that at high RCS flow rates the aggressive ions that enhance the corrosion process near the crack tip will be flushed out, thereby reducing the crack growth rate. The NRC staff agrees with the BWRVIP that crack growth rates are increased at low RCS flow rates. Therefore, the NRC staff concludes that a conservative prediction of crack growth rates at the area of interest can be achieved when the BWRVIA model is used to calculate ECP at the low flow rate of [Content Deleted – EPRI Proprietary]. Based on the review of the data provided in BWRVIP-62, supplemented by the BWRVIP responses, the NRC staff concludes that credit can be claimed for HWC-M when the measured ECP value of the RCS water at the subject location is [Content Deleted – EPRI Proprietary] or below, the total calculated oxidant is [Content Deleted – EPRI Proprietary Information] or less, and the calculated ECP value at a low RCS flow rate [Content Deleted – EPRI Proprietary] is equal to or less than [Content Deleted – EPRI Proprietary].

3.3.3.1 ECP Model for Category 1 Plants

For Category 1 plants, when the ECP values cannot be measured at the location of interest, an appropriate BWRVIA model can be used to estimate ECP at this location. Correlation between the measured ECP value and the calculated total oxidant as a function of secondary variables ([Content Deleted – EPRI Proprietary Information]) using the BWRVIA is essential in assessing IGSCC mitigation at locations where the ECP cannot be measured. As proposed by the BWRVIP, a minimum concentration of feedwater hydrogen will be established such that the calculated value of the total oxidant is [Content Deleted – EPRI Proprietary Information] or less at the location of interest. The NRC staff reviewed the results associated with Category 1 plants and concludes that these plants shall demonstrate that the calculated total oxidant value obtained from the BWRVIA model at the desired location is [Content Deleted – EPRI Proprietary Information] or less and the calculated ECP value at a low RCS flow rate [Content Deleted – EPRI Proprietary Information] is equal to or less than [Content Deleted – EPRI Proprietary]. These calculations shall take into consideration the uncertainties that are associated with the application of the model and the additional margin used to compensate for any depletion of HWC-M at the desired location. For Category 1 plants, the implementation steps that were presented in the BWRVIP supplementary response sent by letter dated December 17, 2004, must be followed to demonstrate that an effective HWC-M is achieved in the RCS water at the desired location.

HWC credit can be claimed for RVIs at all locations where the model predicts an ECP of [Content Deleted – EPRI Proprietary Information] or below and a total oxidant of [Content Deleted – EPRI Proprietary Information] or less, provided that the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account when evaluating the difference between the measured and calculated ECP values.

As stated in Section 3.2.1 of this SE, the data that was obtained from the [Content Deleted – EPRI Proprietary Information] plants show inconsistencies between the calculated and measured ECP values at the lower head region. Therefore, the NRC staff concludes, as discussed in Section 3.2.1, that the BWRVIA model requires validation for RVIs in the lower head region, which can be achieved by installing an ECP probe specifically in this region.

The NRC staff requests that the BWRVIP provide all available information on inspection results to date (e.g., crack growth rates) for any component that is located in a remote location where ECP values are not measured. This data will be useful in assessing the availability of hydrogen at these locations. The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

3.3.3.2 ECP Model for Category 2 Plants

In its response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that since no ECP is measured for HWC-M Category 2 plants, the BWRVIA model is used to estimate the [Content Deleted – EPRI Proprietary Information]. These plants shall derive the ECP value based on ECP measurements in a sister plant, if available, and the details regarding sister plants are discussed in Section 3.2 of this SE.

However, if a Category 2 plant (as listed in Table 3-5 of BWRVIP-62) does not have measured ECP data from a sister plant available, then it shall derive a calculated ECP value that is low enough to assure that an ECP of [Content Deleted – EPRI Proprietary Information] or below is achieved for that plant design. The data plotted in Figure 6 of the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, provides a basis for selecting a bounding value for the calculated ECP for a given plant. The BWRVIA model will be used to calculate the total oxidant. If the total oxidant calculated at other plant locations is less than the concentration for the bounding value for the calculated ECP, then effective mitigation is assured at those locations. This may lead to more conservative ECPs for plants with no measured ECP or sister plant ECP data. The BWRVIP proposed to measure at least two secondary parameters (preferably, [Content Deleted – EPRI Proprietary Information]) to ensure protection from IGSCC. The BWRVIP further states that additional margin is provided in Category 2 plants by increasing the hydrogen injection rate so that the total oxidant from the BWRVIA model is maintained at [Content Deleted – EPRI Proprietary Information] or less and the ECP value at low flow [Content Deleted – EPRI Proprietary Information] is maintained at [Content Deleted – EPRI Proprietary Information] or below.

The NRC staff reviewed the BWRVIP response and concludes that, for Category 2 plants with no measured ECP values, HWC-M credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the HWC credit can be claimed at all locations where the model predicts an ECP of [Content Deleted – EPRI Proprietary Information] or below and a total oxidant of [Content Deleted – EPRI Proprietary Information] or less. However, an ECP probe must be installed to confirm the model prediction at the next refueling outage. If the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number, then the classification of these plants may be changed from Category 2 to Category 1. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured and calculated ECP values. Due to inconsistencies between the measured and calculated ECP values for RVIs located in the lower head region, the NRC staff concludes (as discussed in Section 3.2.1) that the BWRVIA model requires validation for RVIs located in the lower head region. This can be achieved by installing an ECP probe specifically in this region.

The NRC staff requests that the BWRVIP revise BWRVIP-62 to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letter dated December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letter dated December 17, 2004.

3.3.3.3 ECP Model for Category 3a Plants

In its response sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that for NMCA plants (Category 3a), the BWRVIP proposed to measure the ECP value at a given location, and that this [Content Deleted – EPRI Proprietary Information Content Deleted – EPRI Proprietary Information] to ensure the effectiveness of NMCA at that location. The ECP probes will be exposed to reactor water and may be located within the vessel, in the bottom head drain, in the reactor water cleanup system or in a recirculation line. A plant must conduct a hydrogen ramping test in order to determine the effect of feedwater hydrogen on ECP and select the feedwater hydrogen operating point. [

Content Deleted –
EPRI Proprietary Information

].

In addition, the BWRVIP proposed to implement continuous monitoring of two secondary parameters (i.e., [Content Deleted – EPRI Proprietary Information]) in order to ensure the availability of NMCA at the subject location. The BWRVIP stated that a good correlation will be established between the measured ECP value and the secondary parameters so that, in the event of any failure of an ECP probe, the secondary parameters will be used to assess the effectiveness of NMCA at the desired location. The NRC staff agrees with the approach of ensuring adequate NMCA availability at the desired location by maintaining the secondary parameter values at the required threshold levels that correlate to maintaining a measured ECP value of hydrogen of [Content Deleted – EPRI Proprietary Information] or below. The BWRVIP stated that a minimum molar ratio of [illegible]] should be maintained at the measured location in order to achieve a molar ratio of [illegible]] throughout the RVI locations. Based on the data provided by the BWRVIP to date, the NRC staff concludes that credit can be claimed for NMCA plants when the measured ECP values of the RCS water at the subject location is [Content Deleted – EPRI Proprietary Information] or below, the [Content Deleted – EPRI Proprietary Information] or more is maintained at the measured location, and the [Content Deleted – EPRI Proprietary Information].

Establishing a good correlation between the measured ECP value and the total oxidant (calculated using the BWRVIA model) as a function of secondary variables is essential in assessing IGSCC mitigation at locations where the ECP cannot be measured. For Category 3a plants, when the ECP values cannot be measured at the location of interest, an appropriate BWRVIA model can be used to estimate ECP. The BWRVIA model is used to predict the molar ratio at various locations. A predicted molar ratio of [illegible]] or more in non-monitored locations will ensure effective IGSCC mitigation and NMCA for the RVIs.

NMCA credit can be claimed for RVIs at all locations where the BWRVIA model predicts an ECP of [Content Deleted – EPRI Proprietary Information] or below and a molar ratio of [illegible]] or more, provided the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number. However, the NRC staff's approval is required when intending to take credit for an effective NMCA program when a [Content Deleted – EPRI Proprietary Information]. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between measured and calculated ECP values.

For NMCA plants, BWRVIP-62 does not provide sufficient data for measured ECP to demonstrate the validity of the BWRVIA model for RVIs located in the lower head region. Since inconsistencies exist between measured and calculated ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model for NMCA plants by installing an ECP probe specifically in this region as discussed in Section 3.2.1.

For Category 3a plants, the implementation steps that were presented in the BWRVIP supplementary response sent by letter dated December 17, 2004, must be followed to obtain an effective NMCA in the RCS water. The NRC staff recommends that the BWRVIP provide all information on inspection results (i.e., crack growth rates) available to date for any component that is located in a remote location where ECP values cannot be measured. This data will be useful in assessing the availability of NMCA at these locations.

The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

3.3.3.4 ECP Model for Category 3b Plants

In its response sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004, the BWRVIP stated that plants in Category 3b use the [Content Deleted – EPRI Proprietary Information]. Plants will conduct a hydrogen ramping test to determine the the effect of feedwater hydrogen on the [Content Deleted – EPRI Proprietary Information] and select the feedwater hydrogen operating point. During the hydrogen ramping test, the plant shall correlate the [Content Deleted – EPRI Proprietary Information] with a minimum of two secondary parameters listed in Table 3-5, presented in the BWRVIP supplementary response sent by letter dated December 17, 2004.

The BWRVIA model predicts the molar ratio at various locations within the vessel and piping as a function of feedwater hydrogen. The model prediction for the feedwater hydrogen that is required for a [Content Deleted – EPRI Proprietary Information] shall be compared to and verified with the calculated ECP value at the location of interest. A predicted [Content Deleted – EPRI Proprietary Information] or more in the non-monitored locations will ensure effective IGSCC mitigation and NMCA.

The NRC staff reviewed the BWRVIP response and concludes that for Category 3b plants with no measured ECP values, NMCA credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the NMCA credit can be claimed at all locations where the model predicts an ECP of [Content Deleted – EPRI Proprietary Information] or below and a molar ratio of 3 or more.

An ECP probe must be installed to confirm the model prediction at the next refueling outage. If the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number, then the classification of these plants may be changed from Category 3b to Category 3a. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account when evaluating the difference between measured and calculated ECP values. For NMCA plants, BWRVIP-62 does not provide sufficient data for measured ECP to demonstrate the validity of the BWRVIA model for RVIs located in the lower head region. Since inconsistencies exist between the measured and calculated ECP values for the HWC-M RVIs located in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model for NMCA plants by installing an ECP probe specifically in this region as discussed in Section 3.2.1.

The NRC staff requests that BWRVIP-62 be revised to address the information (including figures and tables) provided in the BWRVIP response to Open Item 3.2.5 sent by letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004. Therefore, the NRC staff considers this issue closed when BWRVIP-62 is revised to include the information provided in the BWRVIP letter dated August 1, 2001, as supplemented by letters dated May 19, 2003, and December 17, 2004.

Table 3-1: Primary and Secondary Parameters to be Used in Implementation of BWRVIP-62 for Category 1, 2, 3a and 3b Plants

Category	Primary Parameters	Secondary Parameters
1. HWC-M	[Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information]
2. HWC-M [Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information]
3a. NMCA	[Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information]
3b. NMCA [Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information]	[Content Deleted - EPRI Proprietary Information

Key: FW: Feed Water; MSLR: Main Steam Line Radiation; MS: Main Steam

3.4 Technical Basis for Proposed Inspection Credit

Section 4.0 of BWRVIP-62 discusses crack growth rates in stainless steels and Alloy 182 welds for plants that implement HWC-M and/or NMCA. Based on the information provided, the NRC staff agrees that crack growth rates decrease when ECP values in the RCS water decrease. The FOI in crack growth rates is based on the availability of HWC-M and/or NMCA. Table 4-4 of BWRVIP-62 provides extensive information regarding the cracking history of RVIs and the degree of IGSCC mitigation provided by HWC-M and/or NMCA. The NRC staff reviewed the information and concurs that certain RVIs require higher feedwater hydrogen concentrations than others in order to acquire equivalent protection from IGSCC. Based on the FOI in crack growth rates, the BWRVIP proposed submittal of plant-specific revised inspection intervals for

RVIs protected by HWC-M or NMCA. The NRC staff will review this submittal as it becomes available. The discussion of crack growth rates in welds with exposure to neutron fluences equal to or greater than [Content Deleted - EPRI Proprietary Information] n/cm^2 is found in Section 3.1.3 of this SE.

4.0 CONCLUSION

The NRC staff has completed its review of BWRVIP-62 and concludes that a revised inspection program can be developed for RVIs based on the FOI for plants that have implemented HWC-M. It should be noted that BWRVIP-62 proposes no quantitative revised inspection schedules, and indicates this will be done at a later date. Therefore, at this time, the NRC staff makes no finding on the degree of modification justified over current inspection schedules.

For Category 1 plants, the NRC staff concludes that credit can be claimed for the availability of HWC-M at all locations where the BWRVIA model predicts an ECP of [Content Deleted - EPRI Proprietary Information] or below and a total oxidant of [Content Deleted - EPRI Proprietary Information] or less, when the difference between measured and calculated ECP values is a negative number. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between measured and calculated ECP values. Because of inconsistencies between measured and calculated ECP values for RVIs located in the lower head region, the BWRVIA model requires validation for RVIs in the lower head region. Validation of the BWRVIA model can be achieved by installing an ECP probe specifically in this region.

For Category 2 plants with no measured ECP values, HWC-M credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the HWC credit can be claimed at all locations where the model predicts an ECP of [Content Deleted - EPRI Proprietary Information] or below and a total oxidant of [Content Deleted - EPRI Proprietary Information] or less.

An ECP probe must be installed to confirm model prediction at the next refueling outage. If the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number, the classification of these plants may be changed from Category 2 to Category 1. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value. Due to inconsistencies between the calculated and measured ECP values for RVIs in the lower head region, the NRC staff concludes, as discussed in Section 3.2.1, that the BWRVIA model requires validation for RVIs in the lower head region which can be achieved by installing an ECP probe specifically in this region.

For NMCA plants, a [Content Deleted - EPRI Proprietary Information] in lieu of [Content Deleted - EPRI Proprietary Information] is required which provides extra margin in ensuring effectiveness of the NMCA program. NRC staff's approval is required when intending to take credit for an effective NMCA program when a [Content Deleted - EPRI Proprietary Information].

For Category 3a plants, credit can be claimed for the availability of NMCA with a [Content Deleted - EPRI Proprietary Information] at all locations which provides extra margin in ensuring the effectiveness of NMCA. For Category 3a plants, the NRC staff concludes that the credit can be claimed for the availability of NMCA at all locations where the BWRVIA model predicts an ECP of [Content Deleted - EPRI Proprietary Information] or below and a molar ratio of [Content Deleted] or more when the difference between a measured and calculated ECP value is a negative number. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value. For NMCA plants, BWRVIP-62 does not provide sufficient measured ECP data points for the RVIs in the lower head region to demonstrate the validity of the BWRVIA model. Since inconsistencies exist between the calculated and measured ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model by installing an ECP probe specifically in this region as discussed in Section 3.2.1.

For Category 3b plants with no measured ECP values, NMCA credit may be given for one operating cycle based on acceptable BWRVIA model predictions. The NRC staff concludes that the NMCA credit can be claimed at all locations where the model predicts an ECP of [Content Deleted - EPRI Proprietary Information] or below and a molar ratio of [illegible] or more.

An ECP probe must be installed to confirm model prediction at the next refueling outage. If the difference between the measured and calculated (per the BWRVIA model) ECP values is a negative number, the classification of these plants may be changed from Category 3b to Category 3a. Tolerances in ECP values, which are inherently part of ECP measurements, should be taken into account in evaluating the difference between the measured ECP value and the calculated ECP value. For NMCA plants, BWRVIP-62 does not provide sufficient measured ECP data points for the RVIs in the lower head region to demonstrate the validity of the BWRVIA model. Since inconsistencies exist between the calculated and measured ECP values for the HWC-M RVIs in the lower head region, the NRC staff determined that the BWRVIA model also requires validation for RVIs in the lower head region for NMCA plants. Therefore, the NRC staff requires validation of the BWRVIA model by installing an ECP probe specifically in this region as discussed in Section 3.2.1.

For the downcomer region, the BWRVIA model (discussed in Section 3.2 of this SE) should take into consideration the effect of radiation on the hydrogen-oxygen recombination reaction. These calculations should take into consideration the uncertainties that are associated with the application of the model and the additional conservative margin to compensate for any depletion of HWC-M in this region.

The NRC staff requests that the BWRVIP provide any available information on the current and previous inspection results (i.e., crack growth rates) of any component that is located in a remote location where ECP values cannot be measured. This data will be useful in assessing the availability of HWC-M or NMCA at these locations. In addition, the growth rates of deep cracks should be monitored to verify that adequate protection is achieved in the deep crack region with effective HWC-M or NMCA.

The BWRVIP has agreed to address the following items in its future submittals.

(1) Review of reports addressed in References 3 and 4 of this SE.

(2) Future additional work on refining the BWRVIA models to reduce the inconsistencies of the calculated ECP values.

(3) Research data on the ECP model that is applicable to the lower plenum region.

The NRC staff has reviewed BWRVIP-62 and the associated responses to the Open Items in the NRC staff's initial SE. The NRC staff finds that BWRVIP-62, as modified and clarified to incorporate the NRC staff's comments above, is acceptable for providing a technical basis for inspection credit for BWR RVIs in Category 1 and 3a plants. BWRVIP-62 also provides an acceptable technical basis for allowing Category 2 and 3b plants to take inspection credit for one operating cycle, until an ECP probe can be installed. As discussed throughout this SE, the modifications that are stated in response to the NRC staff's Open Items must be incorporated in the A-version of BWRVIP-62.

REFERENCES

1. BWR Vessel and Internals Project, "Evaluation of Crack Growth in BWR Stainless Steel RVIs (BWRVIP-14)", TR-105873NP, March 1996 (ADAMS Accession No. ML003736932 for non-proprietary version sent July 2000).

2. P. Andresen, "Modeling of Water and Material Chemistry Effects on Crack Tip Chemistry and Resulting Crack Growth Kinetics," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Edited by G. Theus, and J. Weeks.

3. T. Yeh, M. Yu, C. Wang, F. Chu, C. Huang, J. Kao, "A Comparative Study of the Effectiveness of Hydrogen Water Chemistry by Computer Modeling for Chinsan and Kuosheng," *Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL 1997.

4. Y. Wada, N Shigenaka, N. Uetake, S. Uchida, "Numerical Simulation of SCC Environment in a BWR Primary Coolant System", *Proceedings of the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors,* American Nuclear Society, La Grange Park, IL 1997.

5. BWR Vessel and Internals Project, "Modeling Hydrogen Water Chemistry for BWR Applications - New Results (BWRVIP-13)," TR-106068, December 1995 (ADAMS Accession No. ML9908300072).

6. J. Strosnider, U.S. Nuclear Regulatory Commission, letter C. Terry, BWR Vessel and Internals Project, "Safety Evaluation of the "BWR Vessel and Internals Project, Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," EPRI Report TR-113932, October 1999, (TAC No. 5012)" September 15, 2000 (ADAMS Accession No. ML003751105).

7. BWR Vessel and Internals Project, "Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)," TR-113932, October 1999 (ADAMS Accession No. ML993080249).

Principal Contributor: G. Cheruvenki

Date:

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RECORD OF REVISIONS

BWRVIP-62-A	Information from the following documents was used in preparing the changes included in this report: 1. *BWRVIP-62: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection.* EPRI, Palo Alto, CA: 1998. TR-108705. 2. Safety Evaluation of Proprietary EPRI Report TR-1087805, BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62), ADAMS Accession No. ML010370141, January 30, 2001. 3. Project No. 704 – BWRVIP Response to NRC Safety Evaluation of BWRVIP-62, BWRVIP Letter 2001-250, ADAMS Accession No. ML012140408, August 1, 2005. 4. Project No. 704 – Supplement to BWRVIP Response to NRC Safety Evaluation of BWRVIP-62, BWRVIP Letter 2003-149, ADAMS Accession No. ML031430145, May 19, 2003. 5. Project No. 704 – Supplementary Information on Implementation of BWRVIP-62, BWRVIP Letter 2004-532, ADAMS Accession No. ML043560323, December 17, 2004. 6. Safety Evaluation for Electric Power Research Institute (EPRI) Boiling Water Reactor (BWR) Vessel and Internals Project (BWRVIP) Report TR-108705 (BWRVIP-62) BWRVIP-62: BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection, ADAMS Accession No. ML81840740, July 22, 2008. Final Safety Evaluation for Boiling Water Reactor Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection, ADAMS Accession No. 100850008, April 21, 2010.

Table G-1
Revision Details

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Add NRC Safety Evaluation (SE) behind report title page	NRC Requirement for "-A" Topical Reports	Added NRC SE
Revise Citations Page	EPRI – Report Requirement	Added Finetech to preparers, revised report citing format
Revise Acknowledgements Page	EPRI – Report Requirement	Added Finetech as preparer of the "-A" version.
Add Report Summary	EPRI – Report Format	Added Report Summary
Add Record of Revisions	EPRI – Report Format	Added Record of Revisions (summary)
Contents	EPRI – Report Format	Revised Contents to show 4th level headings and to reflect text revisions. Revision bars not shown
List of Tables	EPRI – Report Format	Added Tables 2-1, 3-7 and 3-8
List of Figures	EPRI – Report Format	Added Figures 2-9 to 2-15; Added Figures 3-15 to 3-19
Executive Summary	Consistency with SE	Revised to state that a minimum measured molar ratio of three is recommended to provide additional IGSCC margin and conservatism. Revised "BWRVIP" to "BWRVIA" when referring to the radiolysis/ECP model
Section 1.4 Effect of Flow Rate	NRC Final SE Section 3.1.1, Initial SE Open Item 3.2.2.	Added SE conclusion and updated reference to BWRVIP-64
Section 1.6.1 Effect of ECP on IGSCC	NRC Final SE Section 3.1.4, Initial SE Open Item 3.2.1.	Revised to state the target ECP threshold for inspection relief is ≤ -230 mV(SHE)
Section 1.6.2 Effect of Oxidant Concentration on IGSCC	NRC Request, incorporate information provided by BWRVIP 2004-532.	Provided technical basis for IGSCC mitigation when total oxidant ≤ 3 ppb
Section 1.8 Mitigation of Deep Cracks by HWC or NMCA (new section)	NRC Final SE Section 3.1.2	Inserted discussion of mitigation of deep cracks provided in BWRVIP 2004-532

Table G-1
Revision Details (Continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Section 1.9 Implementation Requirements (new section)	BWRVIP-94, Revision 1	Specifies the classification of this report for implementation under NEI 03-08
Section 1.11 References	EPRI – Report Format and NRC Request	Updated references Added references 1-23 and 1-24
Section 2.2 (BWRVIA) Model Description	NRC Final SE Section 3.2 Initial SE Open Item 3.2.4	Added a description and references for BWRVIA V2.0, which replaced V1.0 in 2003
Section 2.2.4 ECP Calculations	NRC Final SE Sections 3.3.3.1 through 3.3.3.4, Initial SE Open Item 3.2.5	Retained ECP calculations for BWRVIA V1.0 as Section 2.2.4.1 Added 2.2.4.2 for ECP calculations using the Mixed Potential Model for BWRVIA V2.0
Section 2.2.5 Model Output Files	NRC Final Sections 3.3.3.1 through 3.3.3.4, Initial SE Open Items 3.2.4 and 3.2.5	Updated to Version 2.0. Added total oxidant, EMACH and EMACL to output files
Section 2.3 Simulation vs. Measurement	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Section 2.3.2 Validity of V1.0, incorporating BWRVIP 2001-250 Added Section 2.3.3 Validity of V2.0, incorporating BWRVIP 2004-532
Section 2.4 Summary	Information update and clarification	Added new name for AEA Technology Clarified that the discussion was for Mod-HWC
Section 2.5 References	EPRI – Report Format and NRC Request	Updated references Added references 2-31 to 2-35
Table 2-1	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added table provided by BWRVIP 2001-250
Add Figure 2-9	NRC Final SE Section 3.1.1, Initial SE Open Items 3.2.2 and 3.2.5	Added Figure 2-9. Supports the description of the Mixed Potential Model in Section 2.2.4.2 and shows the effect of flow on ECP

Table G-1
Revision Details (Continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Add BWRVIP 2001-250 Figure 3	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-10
Add BWRVIP 2001-250 Figure 4	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-11
Add BWRVIP 2001-250 Figure 5	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-12
Add BWRVIP 2001-250 Figure 6	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-13
Add BWRVIP 2004-532 Figure 1	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-14
Add BWRVIP 2004-532 Figure 2	NRC Final SE Section 3.2, Initial SE Open Item 3.2.4	Added Figure 2-15
Section 3.3 Approach (for Effectiveness Assessment)	NRC Final SE Section 3.3	Revised to incorporate agreements on the attributes of an effective HWC program based on discussions in BWRVIP 2001-250, 2003-149 and 2004-532 and specified in the SE
Section 3.4 Secondary Parameters	Clarification	Restructured text to separately discuss Mod-HWC Plants (3.4.1) and NMCA Plants (3.4.2).
Section 3.5 Implementation Mod-HWC Plants	NRC Final SE Section 3.3	Incorporated SE requirements and commitments from BWRVIP 2004-532.
3.6 Implementation NMCA Plants	NRC Final SE Section 3.3	Incorporated SE requirements and commitments from BWRVIP 2004-532.
3.8 BWRVIP Crack Growth Modeling for Stainless Steel	NRC Final SE Section 3.1.3, Initial SE Open Items 3.1.1 and 3.1.2	Separated discussion by fluence. Section 3.8.1, fluence <5E20 n/cm^2, using BWRVIP-14-A Section 3.8.2, 5E20 ≤fluence ≤3E21 using BWRVIP-99-A.
3.9 BWRVIP Crack Growth Modeling for Nickel-base Alloys	Update to incorporate BWRVIP-59-A	Reference BWRVIP-59-A, noted that the NRC has not approved use of the high purity NWC curve.

Table G-1
Revision Details (Continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
3.10 References	EPRI – Report Format and NRC Request	Updated references Added references 3-21 to 3-23
Incorporate SE Table 3-1 and BWRVIP 2004-532 Revised Table 3-5.	NRC Final SE Section 3.3	Revised Table 3-5
Add BWRVIP 2004-532 Table 1a	NRC Final SE Sections 3.3.3.1 and 3.3.3.2	Added Table 3-7
Add BWRVIP 2004-532 Table 1b	NRC Final SE Sections 3.3.3.3 and 3.3.3.4	Added Table 3-8
Add BWRVIP 2004-532 Figure 4	NRC Final SE Section 3.3.3.1	Added Figure 3-15
Add BWRVIP 2004-532 Figure 5	NRC Final SE Section 3.3.3.1	Added Figure 3-16
Add BWRVIP 2004-532 Figure 6	NRC Final SE Section 3.3.3.3	Added Figure 3-17
Add BWRVIP 2004-532 Figure 7	NRC Final SE Section 3.3.3.3	Added Figure 3-18
Add BWRVIP 2004-532 Figure 8	NRC Final SE Section 3.3.3.3	Added Figure 3-19
4.2 BWRVIP Crack Growth Modeling Factors of Improvement for Stainless Steel	NRC Final SE Section 3.1.3, Initial SE Open Item 3.1.1	Revised discussion for fluence $\geq$5E20 n/cm^2 and $\leq$3E21 n/cm^2 to reference BWRVIP-99-A and to describe potential FOIs.
4.3 BWRVIP Crack Growth Disposition Curve Factors of Improvement for Alloy 182	Update information	Inserted from BWRVIP-59-A that Alloy 182 crack growth rates were conservative for Alloys 82 and 600.
4.6 Add summary of requirements for inspection relief	NRC Final SE	Added Section 4.6 Summary: Effective Implementation of Hydrogen Injection for RVIs.
4.6 Add BWRVIA radiolysis/ECP model run timing	NRC Final SE Section 3.1.5, Initial SE Open Item 3.2.6	Added requirements under Subsections 4.6.2 and 4.6.3 that the model will be run for conditions at the beginning and at the end of the fuel cycle to determine the most conservative conditions for assessing IGSCC mitigation.
4.7 References	EPRI – Report Format and NRC Request	Updated references
Table 4-1	Update information	Updated Table 4-1 references

Table G-1
Revision Details (Continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Table 4-2	Update information	Indicate that FOIs were calculated using BWRVIP-14
Table 4-4	Correct terminology	Change "Protection" to "Mitigation"
Figure 4-1	Difficult to read	Replaced for clarity
Add Appendix A Physical Explanation for BWRVIA Molar Ratio Predictions	NRC Request	Added Appendix A
Add Appendix B NRC (Initial) Safety Evaluation: January 30, 2001	NRC Requirement for "-A" Topical Reports	Added Appendix B
Add Appendix C BWRIP Response to NRC Safety Evaluation: August 1, 2001	NRC Requirement for "-A" Topical Reports	Added Appendix C, BWRVIP 2001-250
Add Appendix D Supplement to BWRVIP Response to NRC Safety Evaluation: May 19, 2003	NRC Requirement for "-A" Topical Reports	Added Appendix D, BWRVIP 2003-149
Add Appendix E Supplementary Information on Implementation: December 17, 2004	NRC Requirement for "-A" Topical Reports	Added Appendix E, BWRVIP 2004-532
Add Appendix F NRC (Interim) Safety Evaluation: July 22, 2008	NRC Requirement for "-A" Topical Reports	Added Appendix F
Add Appendix G, Record of Revisions	BWRVIP requirement for NRC Approved reports	Added Appendix G

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