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BWR Vessel and Internals Project Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62NP)

REPORT SUMMARY

The Boiling Water Reactor Vessel and Internals Project (BWRVIP), formed in June 1994, is an association of utilities focused exclusively on BWR vessel and internals issues. This report provides 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.

Background

BWR availability has been negatively impacted by the IGSCC o austenitic stainless steel piping and, more recently, reactor internal components. As mandated by the 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 HWC process has been developed along two parallel paths to provide reactor internals IGSCC mitigation. The first internals IGSCC mitigation technique, moderate HWC (HWC-M), involves higher hydrogen injection rates in the feedwater compared to the recirculation piping. The second internals IGSCC mitigation technique, noble metal chemical application (NMCA), involves the continuous injection of a small amount of hydrogen to give a hydrogen to oxygen molar ratio >2 plus an occasional batch injection of noble metal compounds that act as catalysts for the various recombination reactions.

Objectives

- To demonstrate that either HWC-M or NMCA provides IGSCC mitigation of BWR internals.
- To demonstrate that inspection relief is justified for BWR internals at plants that have effectively implemented HWC-M or NMCA through the use of crack growth rate factors of improvement FOIs).

Approach

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. Many plants do not have direct ECP measurements available at pertinent locations such as the lower plenum. Even those plants that do have direct measurements

available recognize that such local measurements may not be representative of all potentially susceptible component surfaces. Therefore, it was 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 was developed that can be applied in the absence of direct ECP measurements or as a supplement to direct ECP measurements. For example, ECPs can be calculated using verified computer models, (e.g., the BWRVIP radiolysis/ECP model) that can be directly correlated with measurements of other plant "secondary" parameters, (e.g., oxygen, main steam line radiation levels, etc.) and data from "sister" plants.

Results
Based on the crack growth modeling and radiolysis results, 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 crack growth modeling results would be applied to revise the internals inspection interval established in the various BWRVIP inspection and evaluation (I&E) documents. At a later date, the BWRVIP will propose revised inspection intervals for vessel internals for plants that have implemented either HWC-M or NMCA.

EPRI Perspective
The systematic approach described in this study can be used to verify mitigation of IGSCC of reactor internals with either HWC-M or NMCA. Once IGSCC verification is obtained by using parameters such as ECPs calculated from verified computer models, measurements of other plant secondary parameters, electrochemical and chemical measurements obtained from "sister" plants, etc., the FOI approach can be applied to the current inspection criteria to provide a reduction in inspection frequency. This will lead to significant inspection cost reductions and person-Rem savings with no impact on plant reliability or safety.

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Interest Categories
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Licensing and safety assessment

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BWR Vessel and Internals Project

Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection (BWRVIP-62NP)

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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.

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EXECUTIVE SUMMARY

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.

Detailed safety evaluation coupled with appropriate inspection and evaluation (I&E) guidelines, based on NUREG-0313 Revision 2 for recirculation piping and various BWR Vessel and Internals Project (BWRVIP) products for reactor vessel internals, are in place to ensure continued safe operation through critical monitoring of components' structural integrity. Owing to the difficulties associated with accessibility and the expense of performing inspections on reactor internals, it is clearly desirable to demonstrate that the likelihood for flaw initiation and subsequent propagation due to IGSCC are substantially diminished when proper IGSCC mitigation practices are pursued.

Fortunately, a global environmental IGSCC mitigation technique, hydrogen water chemistry (HWC) has been qualified for the BWR fleet. In fact, the NRC has agreed that HWC implementation provides the basis for relief of inspection requirements for affected piping systems (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 piping with HWC, the HWC process has been developed along two parallel paths for mitigation of reactor internals IGSCC. The first qualified protection technique for reactor internals involves higher hydrogen injection rates than would typically be used to protect piping, i.e., hydrogen injection rates in the range of 1 to <2 ppm in the feedwater compared to typically <1 ppm hydrogen for piping HWC (See Section 3.2.1). This augmented hydrogen injection process is referred to as **moderate HWC (HWC-M)**. The second equally protective technique involves the continuous injection of a small amount of hydrogen plus an occasional batch injection of a small amount of noble metal compounds that act as catalysts for the recombination reactions. This second process is referred to **noble metal chemical application (NMCA)**. (NMCA was also known as noble metal chemical addition, is also sometimes referred to as "Catalyzed HWC" and is commercially known as NobleChem , a patented process of GE Nuclear Energy.) Since either process can protect BWR internals from environmental degradation, then either HWC-M or NMCA implementation at a BWR should allow inspection relief for reactor internals. However, NMCA has some additional benefits as compared to HWC-M:

1. Reduced hydrogen injection rate.
2. Return to NWC operation dose rates, 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.

To provide additional IGSCC margin and conservatism, it is recommended that significantly higher hydrogen to oxygen molar ratios be utilized such as a hydrogen to oxygen molar ratio of four, (e.g., hydrogen/oxygen = 4). In other words, while a hydrogen to oxygen molar ratio of two is certainly sufficient for NMCA, a hydrogen to oxygen molar ratio of four would be recommended for added mitigation margin.

Motivated by successful in-plant demonstrations of HWC-M and NMCA, it is prudent for the BWRVIP to seek similar relief or credit for inspection of BWR internal components that are exposed to this less corrosive environment. This report is designed to supply justification for such inspection relief.

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. Many plants do not have direct ECP measurements available at pertinent locations such as the lower plenum. Even those plants that do have reference electrodes available recognize that such local measurements may not be representative of all potentially susceptible component surfaces. 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, ECPs can be calculated using verified computer models such as the BWRVIP 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 BWRVIP radiolysis/ECP model has been proven to be an effective tool to monitor plant water chemistry conditions. The model has been evaluated and developed for over a decade. Modeling simulations have been performed for 23 BWRs and are in excellent agreement with reliable chemistry measurements obtained from steam and recirculation piping.

The BWRVIP radiolysis/ECP model results can then be used with the BWRVIP empirical stainless steel and nickel-base Alloy 182 weld metal crack growth models. These crack growth models have demonstrated that a factor of at least two reduction in crack growth rate is readily achievable with a HWC availability of 70% based on a stainless steel ECP of –230 mV(SHE). These results indicate that reactor internals IGSCC mitigation can be achieved with HWC-M or NMCA.

A vessel internals inspection program can be developed that uses radiolysis and crack growth modeling results or measured ECPs, and percent hydrogen availability, to provide crack growth rate factors of improvement (FOIs). The FOI calculated for each internal component would then be applied to the current inspection criteria established in the various reactor internals BWRVIP I&E documents. For example, a model calculated FOI of two for a component would clearly suggest that the interval for inspection could be increased by at least a factor of two.

1.0 TECHNICAL BASIS FOR HWC MITIGATION

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).

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 [<10 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 B_4C 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.

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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 from 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).

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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 200 to 400 ppb. However, other model calculations predict hydrogen peroxide concentrations up to 1000 ppb.

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 V_m, i.e., the potential difference between the reference electrode and the working electrode (BWR component surface), and the electrode potential of the reference electrode, E_{ref}, relative to the standard hydrogen electrode, SHE, the ECP of the component can be calculated with the following equation:

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

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.

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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.

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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).

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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.

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1.6 IGSCC/IASCC Mitigation with HWC

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 US 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 1-7 presents results from CERT tests on both thermally sensitized and annealed then irradiated Type 304 stainless steel specimens (1-17). **The primary results of this study indicate that the ECP threshold for IGSCC initiation in annealed then irradiated Type 304 stainless steel is –140 mV (SHE), not –230 mV (SHE).** Obviously, these results also indicate that if the

ECP value of stainless steel in the coolant is sufficiently low to protect thermally sensitized stainless steel, i.e., -230 mV (SHE), protection will also be achieved for non-sensitized components exposed to high neutron fluence.

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 7600 effective full power hours (0.87 EFPY) whereas the HWC tests exhibited no crack initiation in times greater than 17400 hours (1.99 EFPY).

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 50 at the higher ECP. The BWRVIP crack growth model lines are also presented in Figure 1-10.

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 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).

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 ^{16}N, that are produced in the core. As the coolant becomes less oxidizing, the chemical form of ^{16}N 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 ^{16}N 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 ^{16}N 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.

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.

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 NMC 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 g/cm^2 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).

1.8 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 ^{16}N 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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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 Hole Covers (Alloy 182/600)	
Nozzle Butters	
Control Blades	
SRM/IRM Dry Tube Cracking	
Jet Pump Beam Bolts	
Cracking of Low Carbon (304L/316L) and Stabilized Stainless Steels (347/321/348) in Vessel Locations	Late 1980s – present
Core Spray Jumpers	
Creviced Safe Ends	
Shrouds (304L and 347)	
Top Guide (304, 304L, 347)	
Core Support Plate (347)	
Cracking of Internal Core Spray Piping	1980s – present

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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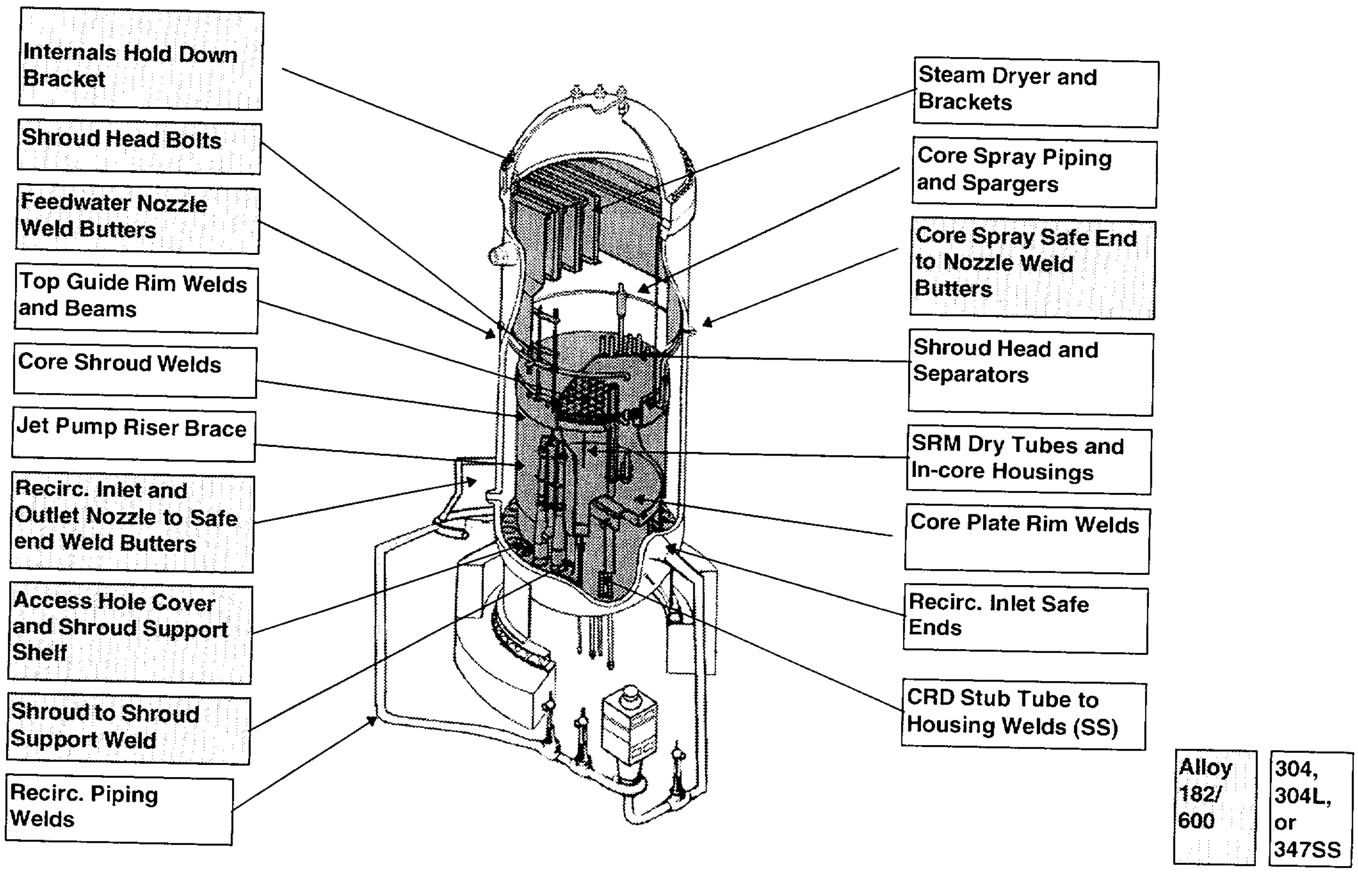

Figure 1-1. Summary Schematic of Components Indicating IGSCC in the BWR (1-2)

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

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

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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 HighVelocities with the New Specimen Configuration (1-12)

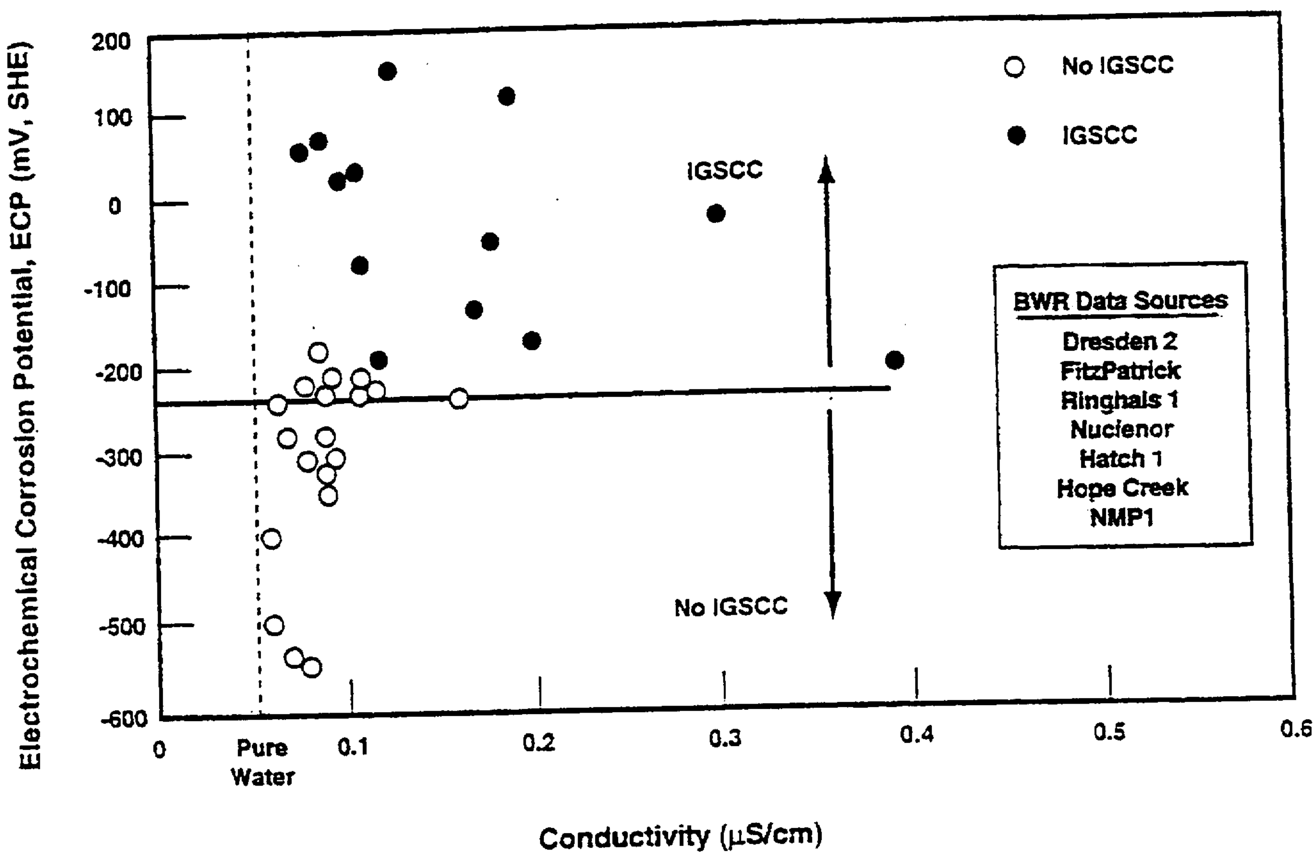
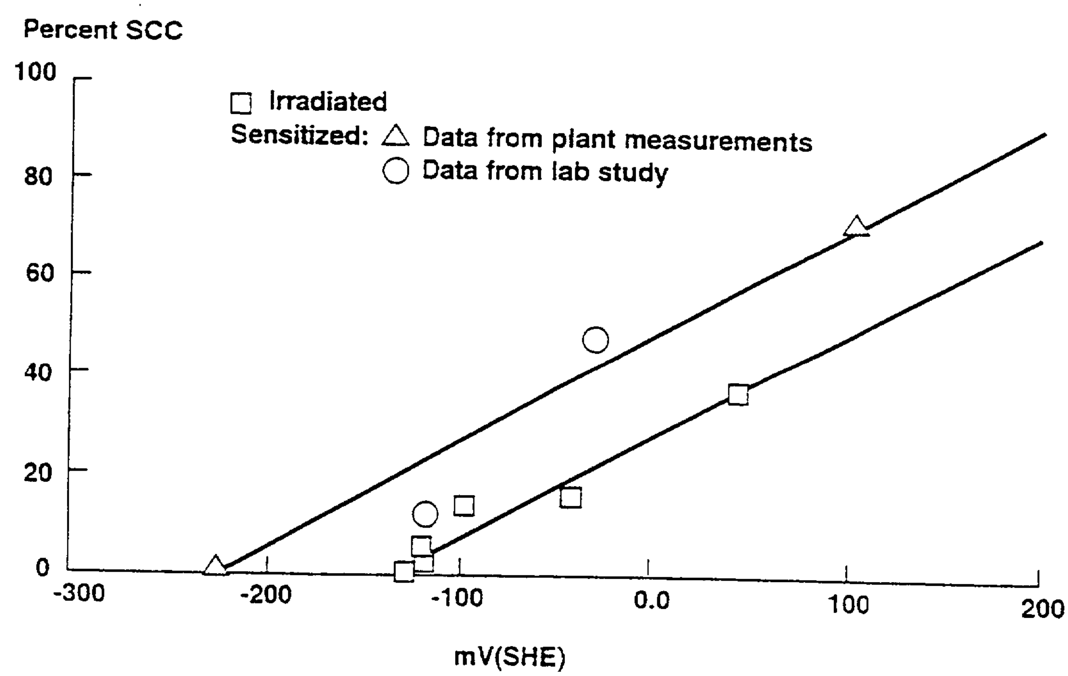


Figure 1-6. CERT Results Supporting IGSCC Protection Potential (1-16)

Notes: Percent SCC is % Intergranular Fracture
Irradiated is solution annealed + irradiated to 1.9×10^{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)

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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)

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

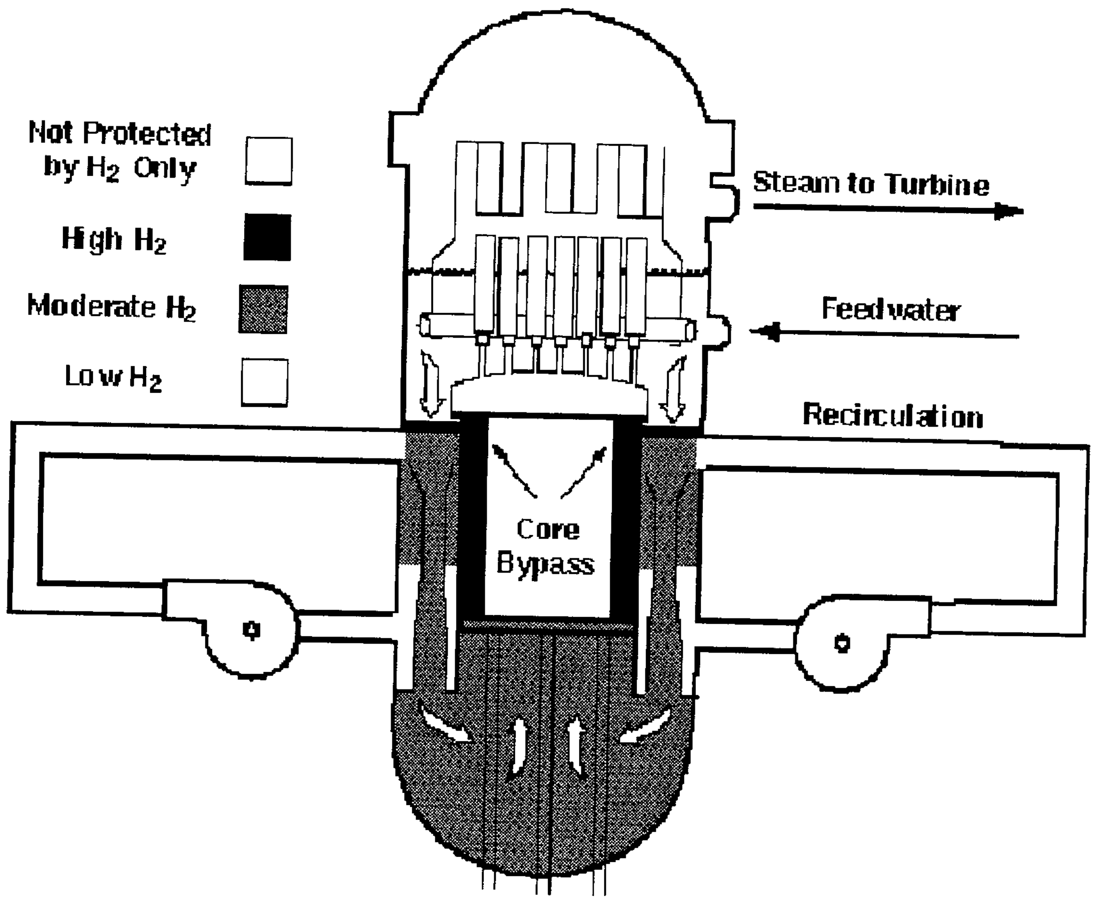

Figure 1-11. Schematic of the BWR Showing the Ranges of Feedwater Hydrogen Required for Reaching -230 mV(SHE) (1-1, 1-16)

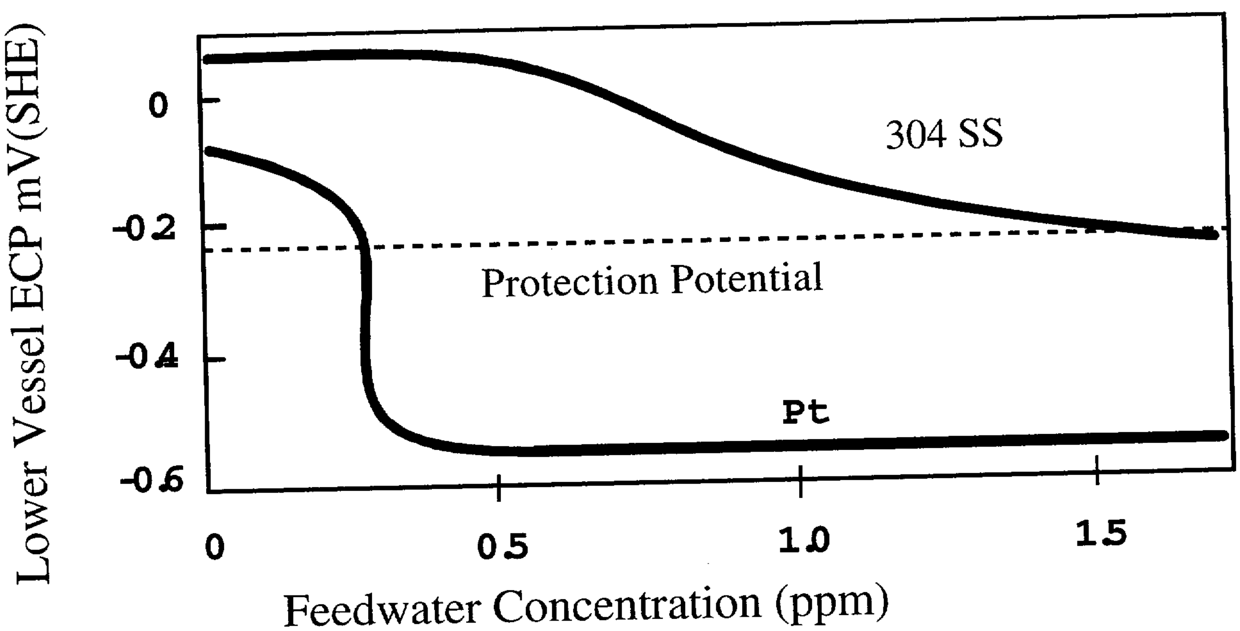

Figure 1-12. Comparison of ECP for Type 304 Stainless Steel and Platinum Surfaces as a Function of Feedwater Hydrogen Concentration (1-19)

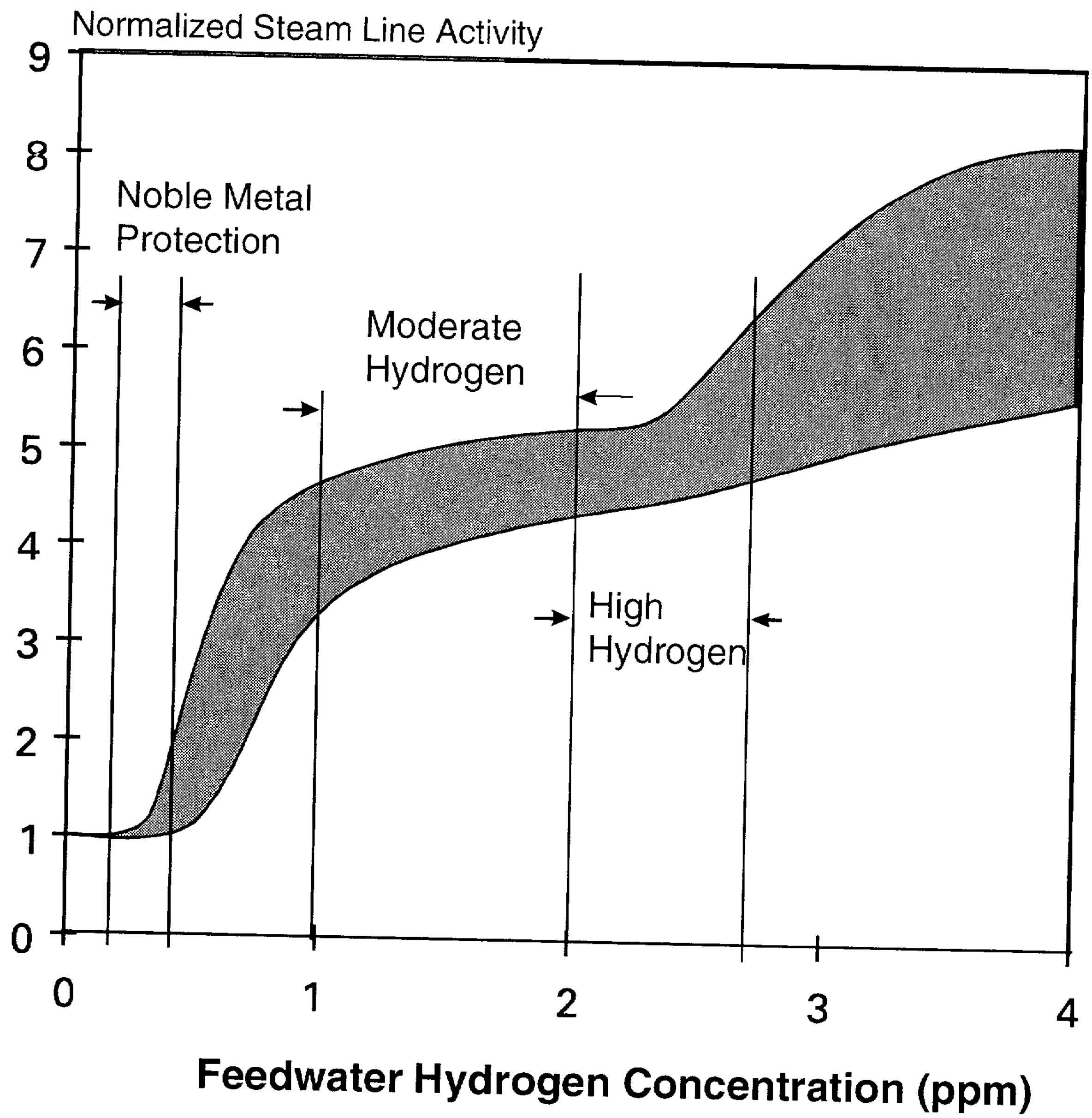

Figure 1-13. Steam Line Activity as a Function of Hydrogen Concentration

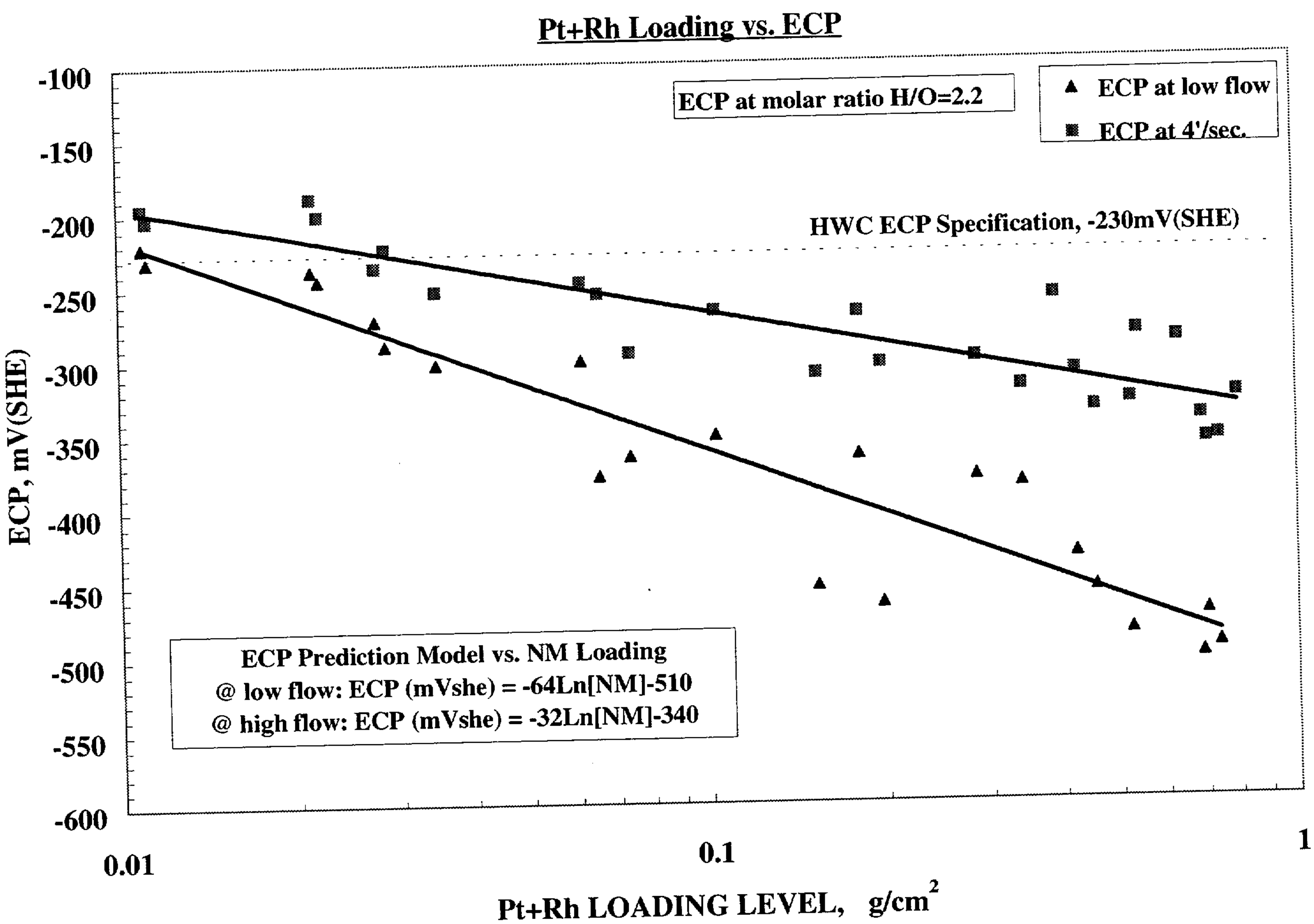

Figure 1-14. ECP as a Function of Pt and Rh Loading Level (1-22).

2.0 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, andrecirculation, 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 a 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   S/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 a 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

The BWRVIP/GE/Harwell radiolysis and ECP computer code (2-28) consists of two main modules. The radiolysis module solves the concentrations of hydrogen, oxygen, hydrogen peroxide and other labile hydrogen-oxygen species. The ECP module calculates ECP values in associated regions based on the water radiolysis results. Two ECP values are calculated: one labeled as HVECP (high velocity ECP) corresponds to actual flow conditions and the other one labeled LVECP (low velocity ECP) assumes that the flow velocity is zero. Crack growth rate in general is correlated to low velocity ECP. Plant drawings and operational state provide input to solve the coupled radiolysis and ECP analysis. The former defines geometric parameters and the latter defines plant radiation field (dose rate) and thermal-hydraulic state (flow).

2.2.1 Radiolysis Model

The radiolysis model calculates, from initial values of concentration, subsequent values resulting from a series of chemical reactions as affected by flow and transport. The radiolysis model input data required by the code includes parameters such as mass flows in different parts of the BWR flow circuit, reactor power, dose rates, carryunder fraction, feedwater hydrogen and oxygen concentrations, and axial values for steam quality and void fraction, as functions of distance in the core channel region.

The flow characteristics and chemistry are linked through the velocity of the liquid, the radiation field, and the void ratio, which are all dependent on position. The void ratio influences the partitioning of hydrogen and oxygen between liquid and vapor, as well as the liquid velocity. The concentration of the chemical species in an element of liquid volume, together with its associated vapor volume in those parts where steam quality is not negligible, is followed by the program. Since the density of the vapor and therefore the radiation energy absorbed per unit volume is about one-twentieth that for the liquid, gas phase radiation chemistry is normally not considered. In addition, the model considers only pure water. The effect of impurities (except for copper) and nitrogen chemistry is not taken into account.

2.2.1.1 Flow Circuit Schematics

The circuit in the computer model consists of 12 regions in the BWR primary system:

- Inside fuel channels
- Inner core bypass (between channels)
- Outer bypass (between channels and shroud)
- Upper plenum
- Steam separators
- Mixing plenum
- Downcomer
- Recirculation piping
- Jet pumps
- Lower plenum
- LPRM
- Bottom head drain line

A diagram of the circuit is shown in Figure 2-1 and the regions are defined in Figure 2-2. The core is divided into two parts, the "channel" region within fuel channels, where the boiling occurs; and the bypass region. The "channel" region comprises two subregions (not shown in Figure 2-2): the lower zone near the bottom of the fuel where the steam quality is less than 1%, and the upper zone where the steam quality is 1% or greater. The bypass region is also subdivided into two regions: "core bypass", i.e., the region outside the fuel channels but within the perimeter of the core, where boiling does not occur; and "outer bypass", i.e., the region bounded by the core and core shroud. The channel, core bypass and outer bypass regions terminate at the top of the fuel.

The upper plenum is the two-phase flow region under the shroud head dome. The channel, core bypass and outer bypass flows mix at the beginning of the upper plenum.

The steam separator region consists of six (6) sub-regions, shown in Figure 2-3, with different flow velocities and residence times for the fluid traversing them:

1. The steam separator riser pipe, up to and including the region of the first stage vanes, where steam and water are a homogeneous mixture.
2. The region after the first stage vanes where water is separated as a film on the inner surface of the pipe.
3. The exit region of the water from the first stage of the steam separator. In this region a small fraction of the steam, highly enriched in dissolved gases, is "carried under" with the water returning to the mixing plenum as a homogeneous mixture.
4. The second stage of water separation.
5. The exit region of the water from the second stage, with virtually no steam carryunder.
6. The third stage of water separation and exit of the steam to the steam dryers.

The mixing plenum is treated by the code as consisting of two sub-regions, before and after the feedwater supply.

The downcomer region is also divided into an upper part and a lower part. In the lower part of the downcomer the flow splits into two portions. A portion of the flow, variable from plant to plant, enters the recirculation system; the second portion of the flow is sucked into the jet pumps. The composition of the flow in the jet pump region is calculated by the code separately. The downcomer annulus is subdivided into separate concentric shells of equal length.

The recirculation region is subdivided by the code into suction, discharge, header ring, riser pipe, jet pump internal riser, and jet pump ram's head. Taking into account the variation in diameter of different segments of the jet pump, the jet pump region is subdivided into throat, diffuser and tailpiece.

The lower plenum region corresponds to the last segment of the flow circuit. This is a non-linear region, because it extends from the exit of the jet pumps to the bottom of the active fuel region. Thus the length of the region does not correspond to a straight distance between two elevations, but rather to a curvilinear segment.

In parts of the circuit where the flow divides and merges later, each branch is treated separately in sequence from the point of separation to the point of recombination. The concentration at the junction is set as the sum of the products of concentration and liquid mass flow fraction for each branch. Concentrations are calculated as functions of distance along the flow path, which comprises all the branches, placed end to end along a single line.

The radiolysis model has the capability of representing one LPRM modified to encase ECP sensors. The modified LPRM is modeled as a series of pipes of various lengths and hydraulic diameters, based upon detailed mechanical drawings.

The bottom head drain line (BHDL) is represented as a set of three pipes in series. A diameter, length, and flow rate characterize each section of pipe. The entrance concentrations to the BHDL are those at the beginning of the upflow in the lower plenum.

2.2.1.2 Model Numerics

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2.2.2 *Dose Rate Calculations*

To determine radiolysis in the flow circuit, radiation fields need to be characterized along the flow path. The current basis of code submodules for gamma and neutron dose rate calculations is a transport calculation (2-29) made on a single reactor, which yielded initial arrays of dose rates. The dose rate arrays are then modified within the code for a given reactor and power distribution to account for local power density and plan -to-plant differences in geometry, (e.g., shroud thickness, annulus width, etc.).

The dose rates in any reactor are obtained based on the following input:

- geometry
- axial power distribution
- axial void distribution
- axial density distribution
- average power in the outer fuel bundles

Input (basis) dose rate axial arrays are:

- Core cross sectional average (gamma and neutron)
- LPRM (gamma and neutron)

- Core equivalents radius (gamma and neutron)
- Outer shroud (gamma and neutron)

Regions where dose rates are calculated are:

- Inside fuel channels
- Inner core bypass (between channels)
- Outer bypass (between channels & shroud)
- Upper plenum
- Downcomer
- Jet pumps
- Lower plenum
- LPRM

2.2.3 Model Input Parameters

All of the details required to obtain the local velocities, length, surface/volume ratio, steam quality, void fraction, and rate constants are available within the program. The model input parameters for an integrated radiolysis and ECP analysis include:

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2.2.4 ECP Calculations

The major ECP determining species in BWRs are oxygen and hydrogen peroxide and hydrogen. Since different components in the BWR circuit require different concentrations of hydrogen in the feedwater system to achieve a given concentration of oxygen and hydrogen peroxide, it is clear that the hydrogen injection requirements necessary to achieve the SCC protection ECP, -230 mV(SHE), vary around the BWR circuit.

ECP values of Type 316 stainless steel were obtained in the laboratory as a function of water chemistry, pre-conditioning of the metal surface, and flow rate, using a rotating cylinder electrode in an autoclave (2-21). The data shows that the ECP behavior of a Type 316 stainless steel electrode is controlled by hydrodynamic water flow conditions, or by the mass transfer rate of reactants, particularly at a low oxygen or hydrogen peroxide level, as well as by the oxidant concentration.

The experimental data were utilized to develop two separate models: ECP as a function of oxygen concentration and ECP as a function of hydrogen peroxide concentration.

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Using the above equation, the calculated ECPs agree well with the measured ECPs with a standard deviation of ±100 mV. When applied to available autoclave ECP data and measured recirculation sample line chemistries, the algorithm matches the available data to ±60 mV. For ECPs in plants operating with NMCA with a hydrogen to oxygen ratio >2, it is assumed that the ECP is <-230 mV(SHE) as shown in Figure 1-14. One convenient assumption is that the H_2 and oxidants react so rapidly at the surface that either a) the H_2 disappears or b) the oxidants disappear. This assumes that there is adequate noble metal at the surface.

2.2.5 Model Output Files

The BWRVIP/GE/Harwell radiolysis/ECP model produces the following output files to evaluate hydrogen injection performance guiding plant HWC operations:

- Main stream values of location, gamma and neutron dose rates, concentrations of hydrogen, oxygen, and hydrogen peroxide, bulk velocity, ECP, and molar ratio of hydrogen to oxidant

- Main stream values of location and concentrations of ions and radicals

- Drain line and LPRM values of location, gamma and neutron dose rates, concentrations of hydrogen, oxygen, and hydrogen peroxide, bulk velocity, ECP, and molar ratio. Values provided at sensor locations.

- Main stream values of location, mass transport coefficient, H_2O_2 decomposition rate constant, kinetic portion of H_2O_2 decomposition rate constant, mass transfer portion of H_2O_2 decomposition rate constant, quality, void ratio, void fraction, hydraulic diameter, velocity, and Reynolds number

- Steam concentrations of hydrogen and oxygen. Recirculation header hydrogen, oxygen, H_2O_2, oxidant, ECP, and molar ratio

- Pressure vessel stream values of location, gamma and neutron dose rates, concentrations of hydrogen, oxygen, and hydrogen peroxide, bulk velocity, ECP, and molar ratio

- Central stream of downcomer values of location, gamma and neutron dose rates, concentrations of hydrogen, oxygen, and hydrogen peroxide, bulk velocity, ECP, and molar ratio

2.3 Simulation vs. Measurement

Experimental measurements of hydrogen and oxygen dissolved in the recirculation lines and condensed steam were compared with corresponding values calculated with the radiolysis model. Results of water chemistry measurements performed at four BWRs (Duane Arnold, Fitzpatrick, Pilgrim and Quad Cities-2) were used. With the exception of Quad Cities-2, these results have been published (2-30). Since the oxygen measured at the end of the sample lines is the sum of the oxygen dissolved in the stream and the oxygen generated by decomposition of hydrogen peroxide, the measured value is compared with the calculated concentration of oxidant, i.e., the sum of the calculated concentration of oxygen and approximately half the calculated concentration of hydrogen peroxide. Any possible oxygen consumption in the sample line is not accounted for in the calculation.

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 0.5 and 1.5 ppm feedwater hydrogen. The predicted minimum in the steam hydrogen occurs at approximately 0.3-0.4 ppm feedwater hydrogen, while experimentally the minimum occurs at ~0.6 ppm. 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.

The model predicts significant differences between the recirculation line hydrogen of different reactors, Figure 2-6. At high feedwater hydrogen, the slope of the calculated curves is determined by the ratio of the feedwater flow to the core flow. Hydrogen in the feedwater is diluted with the mixing plenum water. This mixture is the main source of hydrogen for the recirculation lines. As shown, the model tends to under calculate hydrogen, providing conservative predictions. As with the hydrogen, there are significant plant-to-plant differences in the oxygen. Figure 2-7 shows that the model calculated oxidant might either be higher or lower than measurements.

Plant ECP measurements were obtained from modified LPRMs that contain ECP sensors. Analyses reported in the BWRVIP ten-plant study indicate that the concentrations of hydrogen, oxygen and hydrogen peroxide, and the corresponding ECP values, are generally different inside and outside the LPRM (2-20). Variation in these ECP differences is dependent upon the local flow rate. It was also observed that at the top of the core the ECP is not sensitive to sensor position. In other words, a slight misplacement of the sensors is not significant. On the other hand, the sensors are very sensitive to their position below the core plate, especially at moderate to high feedwater H_2 injection rates.

Figure 2-8 shows the comparison of model calculation vs. plant measured data including 162 data points from twenty (20) sensors at mid-core, core plate, recirculation flange and drain line locations in six (6) plants. The measurements agree reasonably well with calculated results considering uncertainties of all involved variables.

2.4 Summary

GE Nuclear Energy, AEA Technology 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 at hydrogen levels between 0.8 and 2.5 ppm 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 (up to 3 ppm).

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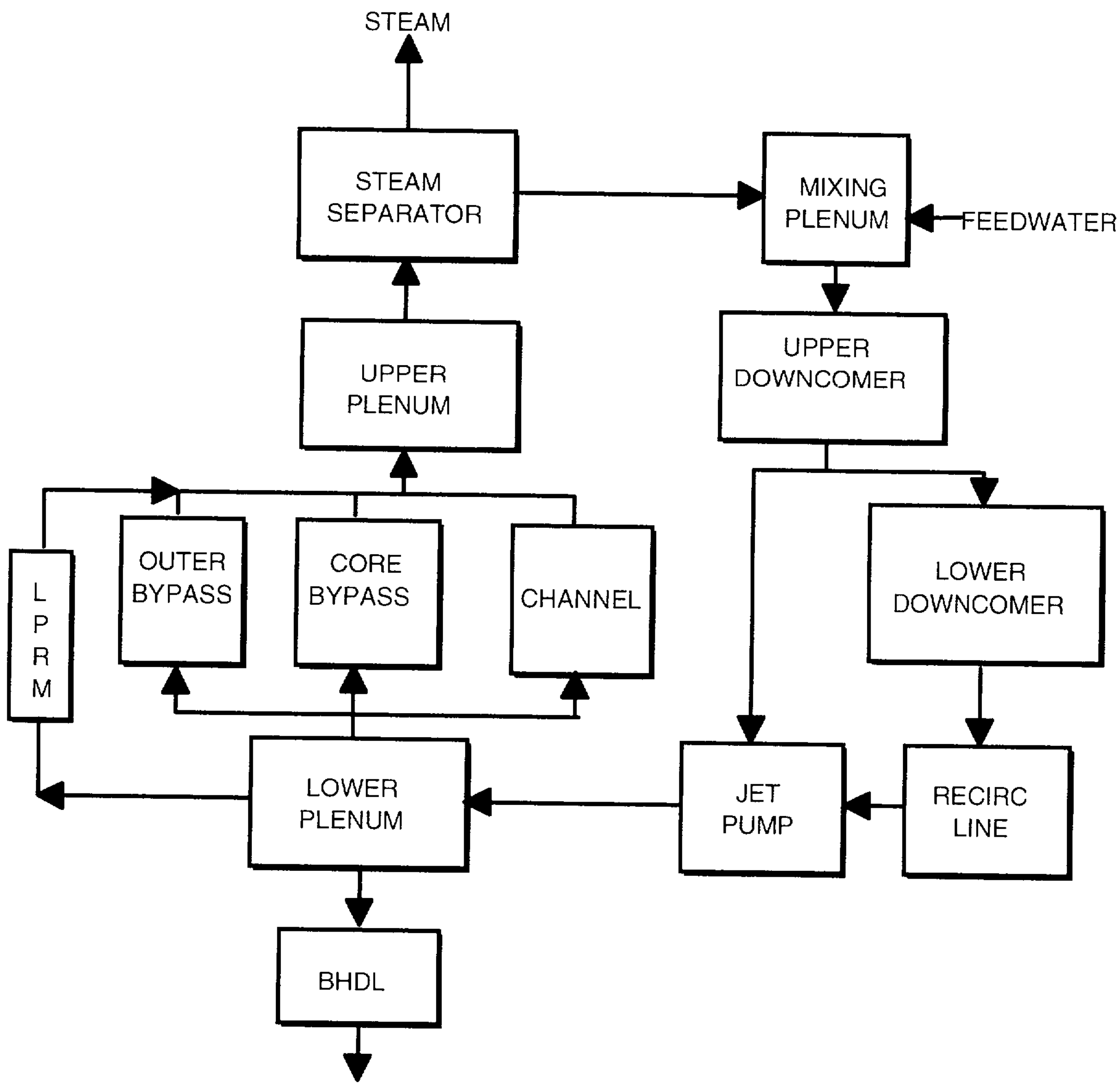

Figure 2-1. Computer Model of BWR Primary System

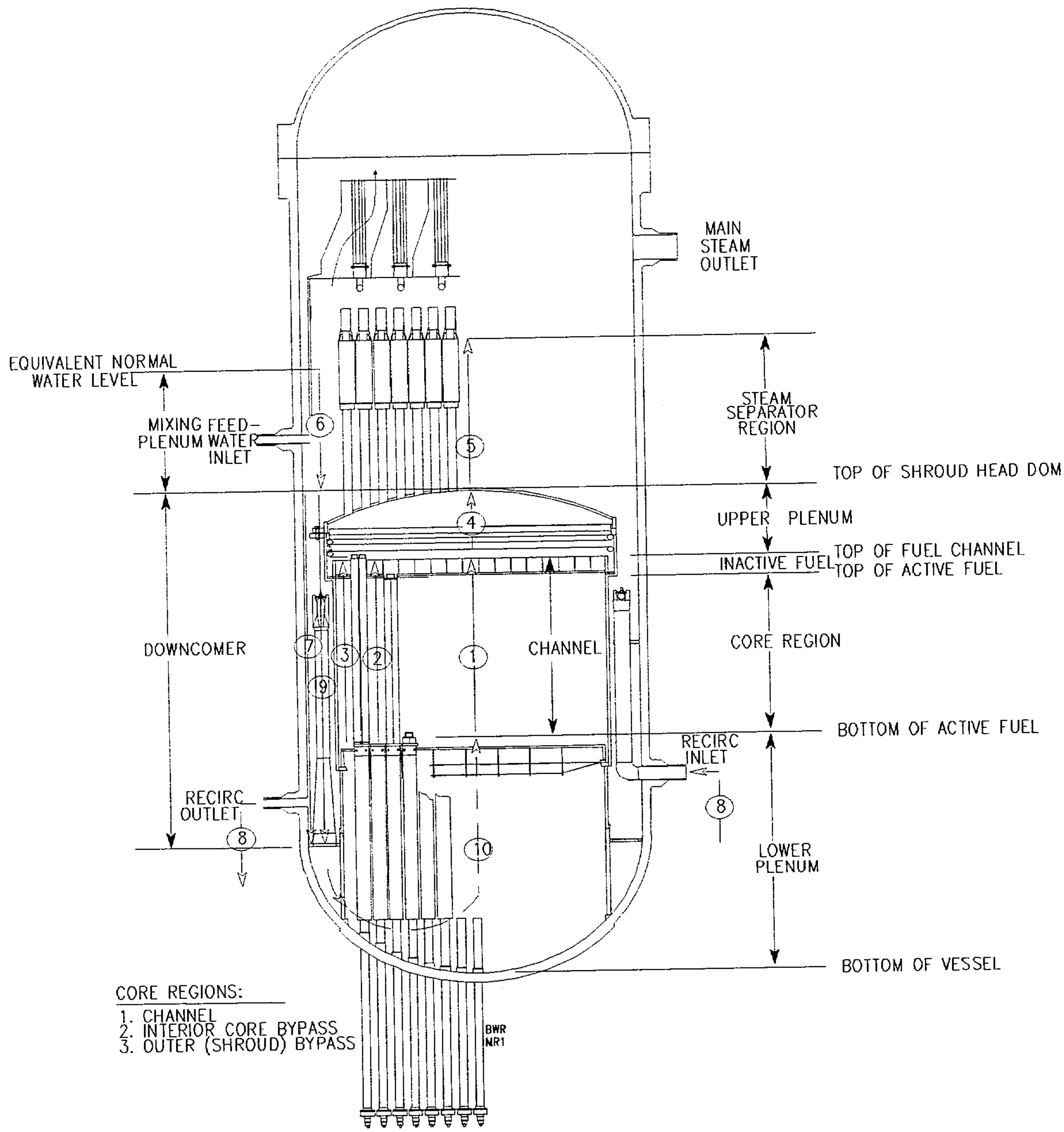

Figure 2-2. Radiolysis Model Region and Circuit Identification

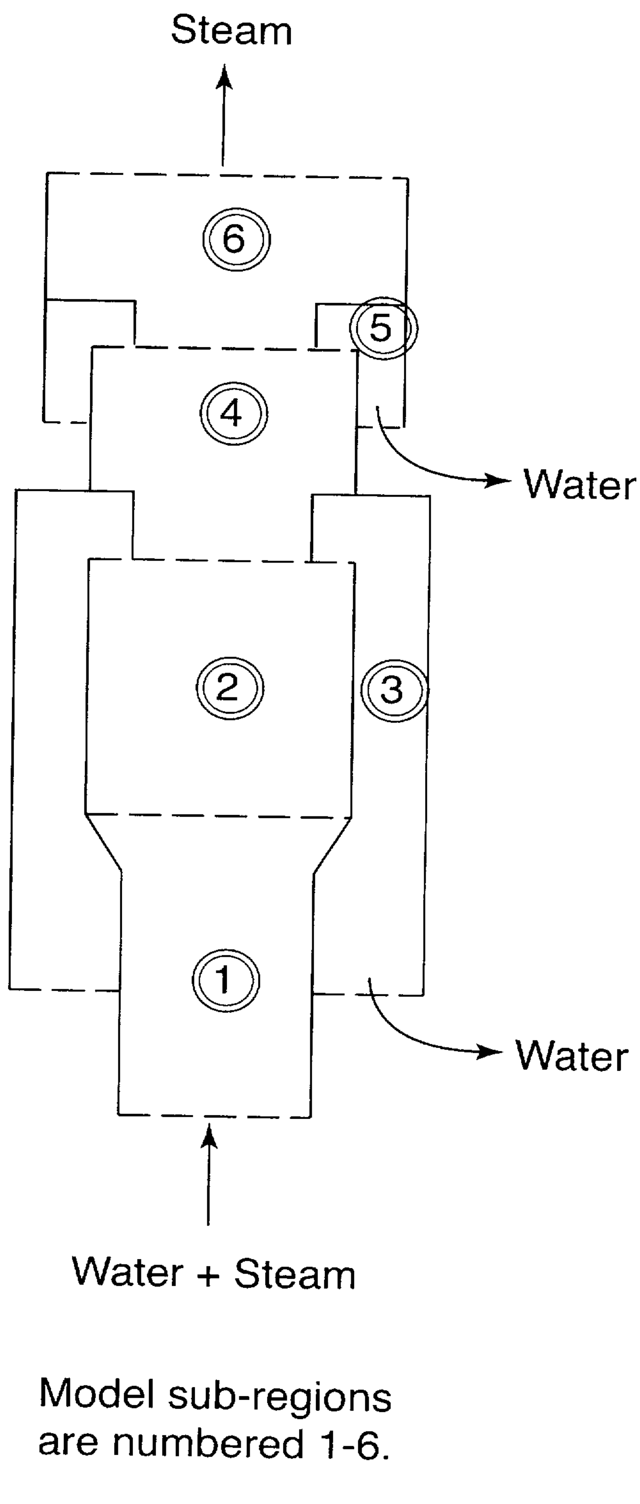

Figure 2-3. Simplified Schematic of Steam Separator

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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

3.0 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.

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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).

The global view of the benefits of HWC i 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).

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In summary, during the past decade, several plants have operated with HWC during multiple operating cycles. One plant, Duane Arnold, has met 90% 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 90%. 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. Since water chemistry and ECP change with location inside the RPV, predictive computer based models (Section 2) will be used to determine chemistry conditions and ECP in various regions as a function of hydrogen feed rate. The models will be benchmarked against ECP measurements made at the plant or at other plants that are radiolytically identical and operationally similar. Such plants are referred to as "sister plants" in this report, as described in Section 3.7. 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.

The method used at a particular plant will depend on the HWC process (HWC-M or NMCA) and on the availability of ECP measurements. Three categories of plants are considered:

1. Plants in Category 1 would use the approach summarized in Table 3-5 to ensure that the vessel internals are effectively mitigated. A radiolysis/ECP model would be used to estimate ECP in regions of concern. The model would be benchmarked to plant measurements at a specific location. The hydrogen injection rate or feedwater hydrogen concentration and the normalized MSLR level would be monitored as discussed in Section 3.5 to verify continued protection. Either plant specific or sister plant correlation among ECP, normalized MSLR and feedwater hydrogen could be used to verify protection (discussed in Figures 3-4 and 3-6).

2. Plants in Category 2 with no ECP calibration data need to use the radiolysis/ECP model to estimate the feedwater hydrogen concentration required to protect the vessel internals as shown in Table 3-5. Since no ECP calibration data is available, then an additional margin on the estimated feedwater hydrogen may be required to ensure protection. The hydrogen injection rate or feedwater hydrogen concentration and the normalized MSLR fields would be monitored to verify continued protection, as discussed in Section 3.5. These plants would use fleet wide data on the correlation between ECP, normalized MSLR and feedwater hydrogen, (e.g., Figure 3-5), to verify continued protection.

3. Plants in Category 3 (NMCA) would use either measurements of the hydrogen to oxygen molar ratio or ECP from a post-NMCA hydrogen ramping test to select the hydrogen injection rate or feedwater hydrogen concentration required to protect vessel internals, Table 3-5. These plants would monitor the hydrogen injection rate or feedwater hydrogen concentration and the catalytic activity of plant surfaces to verify continued protection. This would be done by either

monitoring the ECP on a surface that was treated during noble metal application, or by periodically removing samples that had been treated during application and determining the catalyst loading. The radiolysis model could be used to predict hydrogen to oxygen molar ratios at specific in vessel locations. Data indicates that an ECP <-230 mV(SHE) can be achieved at any location when the molar ratio is >2 and there is sufficient catalyst loading.

3.4 Secondary Parameters

As noted in Section 3.3, it is desirable to have other methods for determining the effectiveness of HWC. One method that appears to be effective is the monitoring of plant chemical parameters that are affected by HWC and, thereby, establishing a correlation between the measured values for those secondary chemical parameters and HWC effectiveness. Secondary parameters are alternate and confirming chemical parameters such as feedwater hydrogen flow rate, normalized MSLR, MS line oxygen content, etc. that can be directly related to primary parameters such as ECP and hydrogen to oxygen molar ratios to verify environmental conditions of IGSCC mitigation. Secondary parameters are used when primary parameter data is not available. **It is important to emphasize that no single secondary parameter should be considered by itself as the sole monitor of HWC performance.** Rather, a set of such parameters should be identified and calibrated for each plant and monitored on a regular basis as shown in Table 3-5. Several parameters that have been shown to correlate with HWC performance are discussed below. This parameter set should be considered as representative rather than exhaustive, since the instrumentation available, the HWC operation, and the locations of interest will vary from plant to plant.

The amount of hydrogen required to reduce the ECP to <-230 mV at any material location in a plant is highly plant specific, Table 3-2. In any plant, the ECP decreases as the dissolved hydrogen injection rate increases. As discussed in Section 1.7, since NMCA provides a catalytic surface so that the recombination of hydrogen and oxidizing species occurs at the surface when the molar ratio of hydrogen to oxygen is greater than two. Therefore, less hydrogen is required to achieve the same decrease in ECP with NMCA.

Under HWC-M, as the bulk coolant becomes more reducing, other water chemistry parameters also respond to changes in the oxidizing power of the coolant. Therefore, the response of these parameters will also provide an indirect indication of the ECP of a component. Such responses may include changes in the oxidation states, i.e., valence, of specific ionic species in the coolant. Two species that demonstrate such transitions as the coolant changes from more oxidizing to more reducing are oxygen and nitrogen compounds.

3.4.1 Hydrogen, Oxygen and Their Molar Ratio

Dissolved oxygen concentration in the coolant can provide an indication of HWC's effectiveness at the sampling source. Oxygen measurements can be used to benchmark the radiolysis model for a particular plant. The molar ratio of hydrogen to oxygen can be used to predict the effectiveness of NMCA at a particular location.

However, it should be noted that due to the mobility of NMCA compounds, significant effects on dissolved oxygen measurements obtained from sample lines could occur for NMCA BWRs, i.e., the measurement results obtained in NMCA coated sample lines would be non conservative.

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3.4.2 Nitrogen-16 Isotope and Main Steam Line Radiation

Nitrogen in water can exist in a range of oxidation states from nitrate (oxidizing conditions) to ammonia (reducing conditions). When the coolant in the lower plenum region becomes sufficiently reducing, the nitrogen equilibrium rapidly shifts in the direction of the more volatile ammonium state. This can result in a pronounced increase in the level of radioactive ^{16}N isotope in the main steam, resulting in large increases in the MSLR levels as indicated by the MSLR monitors (3-3). Increases by a factor of four or more can occur in some BWR designs. This response has two characteristics that make this ^{16}N measurement an effective secondary parameter that is useful for correlation to the ECP. These are:

1) the magnitude of the shift, which makes the transition to a sufficiently reducing condition clearly identifiable, and,

2) the upper plateau in the measurement once reducing conditions are achieved. (It should be noted that based on two high hydrogen injection tests conducted at two BWRs, there can be a second plateau at ~8x at >2.5 ppm hydrogen in the feedwater.)

The increase in MSLR dose due to ^{16}N is an indicator of the reducing nature of the bulk environment. While ^{16}N may not be a particularly useful parameter to monitor the effectiveness of NMCA, a process that only affects the local environment at the metal surface, it may be possible to correlate a small increase, i.e., 10 to 20%, in MSLR to the achievement of the desired molar ratio of hydrogen to oxygen in the reactor vessel.

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.

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More specifically, a program has been performed at the BWR-3 Santa María de Garoña to determine the lower plenum ECP as a function of hydrogen injection rate (3-16). Modified LPRMs were installed with ECP reference electrodes at six locations in the lower plenum region to conduct this ECP measurement program. The locations were chosen at different elevations and radial core positions to provide ECP measurements as a function of lower plenum position.

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3.4.3 Main Steam Oxygen

Similar attempts to develop a correlation between MS oxygen and lower core, bottom head drain, upper core and recirculation piping ECP also yield promising results, Figures 3-9 through 3-11.

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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.

3.5 Monitoring of Secondary Parameters for HWC-M BWRs

3.5.1 Secondary Parameters

Table 3-5 lists secondary parameters that may be monitored to provide an indication of the ECP in the vessel for plants on HWC-M. Some of those parameters are operational variables that will be nearly continuously monitored; others are parameters that are tracked for other reasons but that have been demonstrated to be complementary to ECP/HWC-M effectiveness monitoring. These parameters are not applicable to plants using NMCA as discussed in Section 3.3.

The HWC-M secondary parameters of interest are:

- Feedwater hydrogen flow rate or concentration

- Reactor coolant dissolved oxygen
- Reactor coolant dissolved hydrogen
- Main steam line radiation level
- Main steam line oxygen content

As discussed in Section 3.3, all plants using HWC-M need to monitor feedwater hydrogen and MSLR fields to ensure continued protection.

3.5.2 Frequency of Monitoring Secondary Parameters

Secondary parameters listed in Section 3.5.1 are parameters that will generally be monitored on a regular basis for a variety of reasons, including checks on operation of HWC-M hydrogen injection equipment, for radiation safety, or as a part of normal plant water chemistry controls. The inclusion of one or more of those parameters as secondary parameters for monitoring the effectiveness of HWC-M may increase the frequency of the measurement or calculation to demonstrate continuing IGSCC mitigation. The frequency requirements would be developed on a case by case basis.

3.5.3 Calibration of HWC-M Plants

With the exception of "sister plants" (see Section 3.7), the above secondary parameters can provide a method of demonstrating HWC-M effectiveness based upon a one-time correlation to a direct measurement of ECP. The calibration will consist of the development of a correlation between the measured secondary parameter and the ECP. Ideally this calibration will be performed over a wide range of values. Monitoring options for plants with no ECP calibration data are discussed in Section 3.3. The monitoring requirements would also be developed on a case by case basis.

3.6 Monitoring for Secondary Parameters for NMCA BWRs

NMCA provides IGSCC mitigation to surfaces that are characterized by the deposition of catalytic material, i.e., non-treated surfaces will be characterized by dramatically different corrosion potentials. Since the bulk coolant will not reflect the presence of NMCA, secondary parameters that depend on bulk changes will be ineffective with NMCA plants. The most pronounced of these parameters is MSLR. Because the bulk chemistry is less affected under NMCA, and less hydrogen is required to achieve IGSCC mitigation, significant increases in main steam ^{16}N levels is not expected to occur with NMCA. Therefore, monitoring of MSLR levels will not be particularly useful in demonstrating NMCA effectiveness.

Effectiveness of NMCA is dependent on the hydrogen to oxygen molar ratios present in the regions of concern. Ratios exceeding two are required to demonstrate effectiveness.

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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 theradiolysis model to demonstrate such similarities include (3-8):

1. Plant characteristics

    a. Thermal rated power
    b. RPV internal diameter
    c. Number of fuel assemblies
    d. Active core length
    e. Core average rated power density
    f. Core average heat generation at rated power
    g. Core outer shroud diameter
    h. Downcomer width
    i. Core shroud thickness
    j. Number of jet pumps
    k. Jet pump center line distance from core center

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

   a. Core flow rates
   b. Feedwater flow rates
   c. In-vessel flow rates, (e.g., channel, bypass, jet pump, etc.)
   d. Residence time, (e.g., channel, bypass, jet pump, upper plenum, lower plenum, upper downcomer, recirculation, etc.)
   e. Gamma dose rate factors, (e.g., upper plenum/downcomer, downcomer, lower plenum)

The radiation levels in the downcomer region have a strong effect on the rate of the hydrogen-oxygen recombination reaction. For a particular plant, the radiation level will vary throughout core life. Therefore, it is expected that the actual level of mitigation achieved in, for example, the lower plenum would vary through core life, for a particular level of hydrogen injection. Since this effect could be expected for an individual plant, it could make comparisons between even sister plants more difficult, since the response of both plants will vary with time.

3. Water chemistry

   a. Copper content (that will be mainly determined by condenser material)

Copper contamination in BWR coolant water can result from the copper alloy condenser tube corrosion. Since the copper ion is an additiona cathodic reactant in the coolant, high copper content in the coolant will tend to reduce the effectiveness of HWC. A copper containing coolant will be more oxidizing for a given level of hydrogen injection than would otherwise be the case, in otherwise identical conditions.

In summary, while HWC-M or NMCA data at similar plants may provide valuable indications of performance that could be expected at a particular plant, the determination of similarity requires a radiolysis model evaluation. Significant differences in one or several of the parameters discussed above can cause apparently identical "sister" plants to respond differently to hydrogen injection. Candidate sister BWRs are characterized by radiolysis equivalents that typically reflects plants with nearly identical geometric configuration, system operation and water chemistry parameters.

3.8 BWRVIP Crack Growth Modeling for Stainless Steel

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 (3-19). The model equation has the following form:

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

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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.

3.9 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, several utilities required disposition actions to evaluate the consequences of crack propagation on the structural margin of the component. Data obtained from nickel-base alloy fracture mechanics specimens were used to support these specific disposition efforts. EPRI/BWRVIP is in the process of collecting and reviewing Alloy 182 crack growth data to better assess crack growth rates and subsequently issuing crack growth disposition curves (3-21). Based on screened Alloy 182 data, disposition curves have been developed by GE for three basic BWR environments: (1) NWC at or below the EPRI Action Level 1 conditions, (2) NWC with conductivity restricted to 0.15 S/cm or lower and (3) HWC that meets EPRI guidelines. Table 3-6 summarizes these equations.

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3.10 References

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3-2 Modeling Hydrogen Water Chemistry for BWR Applications – New Results, EPRI, BWRVIP-13, EPRI TR-106068, Palo Alto, CA, December 1995.

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3-17 M. Pytel, "Calculation Package – Development of Relationship Between ECP and Normalized Main Steam Line Radiation (MSLR) for Sant María de Garoña," EPRI News, September 11, 1998.

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Table 3-1

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

Plant Status	**US 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

Summary of Feedwater Hydrogen Addition Rates, in ppm, Required to Reach -230 mV (SHE) in the Indicated Regions of the Reactor Coolant System (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

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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Table 3-5

Example of Primary and Secondary Parameters for BWR HWC Categories

Category	Primary Parameters	Secondary Parameters
1 (HWC-M)	Measured ECP	Feedwater hydrogen flow rate or concentration
		Normalized MSLR or MS line oxygen content
		Reactor coolant oxygen or hydrogen conten
2 (HWC-M, no ECP measurements)	Estimated ECP from Radiolysis/ECP Model	Feedwater hydrogen flow rate or concentration
		Normalized MSLR or MS line oxygen content
		Reactor coolant oxygen or hydrogen conten
3 (NMCA)	Measured H_2:O_2 molar ratio or measured ECP	Feedwater hydrogen flow rate or concentration
		ECP or catalyst loading on a noble metal treated surface
		H_2:0_2 Molar Ratio Radiolysis/ECP Model

Table 3-6

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

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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 María de Garoña ECP and Normalized MSLR Correlation for Six Different LPRM Locations (3-17)

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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)

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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 S/cm) (3-21)

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

4.0 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).

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 ISI relief.

Such a reduction is consistent with the requested ISI guidelines of a factor of two reduction in ISI frequency for all categories of piping and it is also consistent with the water chemistry improvements that apply t 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 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.

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The results of this analysis suggest that a FOI of two is readily obtainable over a relatively wide range of HWC availability and ECPs. For example, from Figure 4-1, a HWC availability of only 75% and a reduction in material ECP to only –100 mV (SHE), a FOI of two in crack growth rate retardation could be obtained. Similarly a 70% HWC availability and a reduction in material ECP to −150 mV (SHE) would provide the same IGSCC benefit. Other validated crack growth models such as PLEDGE may be used for generating similar FOI tables.

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.

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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" 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.

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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 References

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4-16 "Noble Metal Chemical Addition 10 CFR 50.59 Safety Evaluation for Duane Arnold Energy Center (BWRVIP-37)," EPRI TR-108458, Palo Alto, CA, July 1997.

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

Component	BWRVIP Report	EPRI Report	Date
Core Shroud	BWRVIP-01	TR-107079	October 1996
Core Shroud	BWRVIP-07	TR-105747	February 1996
Core Spray	BWRVIP-18	TR-106740	July 1996
Core Plate	BWRVIP-25	TR-107284	December 1996
Top Guide	BWRVIP-26	TR-107285	December 1996
Standby Liquid Control System/Core Plate P	BWRVIP-27	TR-107286	April 1997
Shroud Support	BWRVIP-38	TR-108823	September 1997
Jet Pump Assembly	BWRVIP-41	TR-108728	October 1997
LPCI Coupling	BWRVIP-42	TR-108726	December 1997
Lower Plenum	BWRVIP-47	TR-108727	December 1997
Vessel ID Attachment Weld	BWRVIP-48	TR-108724	February 1998

Table 4-2

BWRVIP Crack Growth Modeling Factors of Improvement for Stainless Steel
As a Function of HWC Availability for an ECP

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Table 4-3

BWRVIP Disposition Curve Factors of Improvement for Alloy 182
As a Function of HWC Availability at an ECP of mV(SHE)

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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)

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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 (cont.) (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 (cont.) (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 (cont.) (4-16)

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Stainless Steel IGSCC Crack Growth Rate Factors of Improvement - BWRVIP-14
0.3 S/cm 15 C/cm2 27.5 MPa m 288C

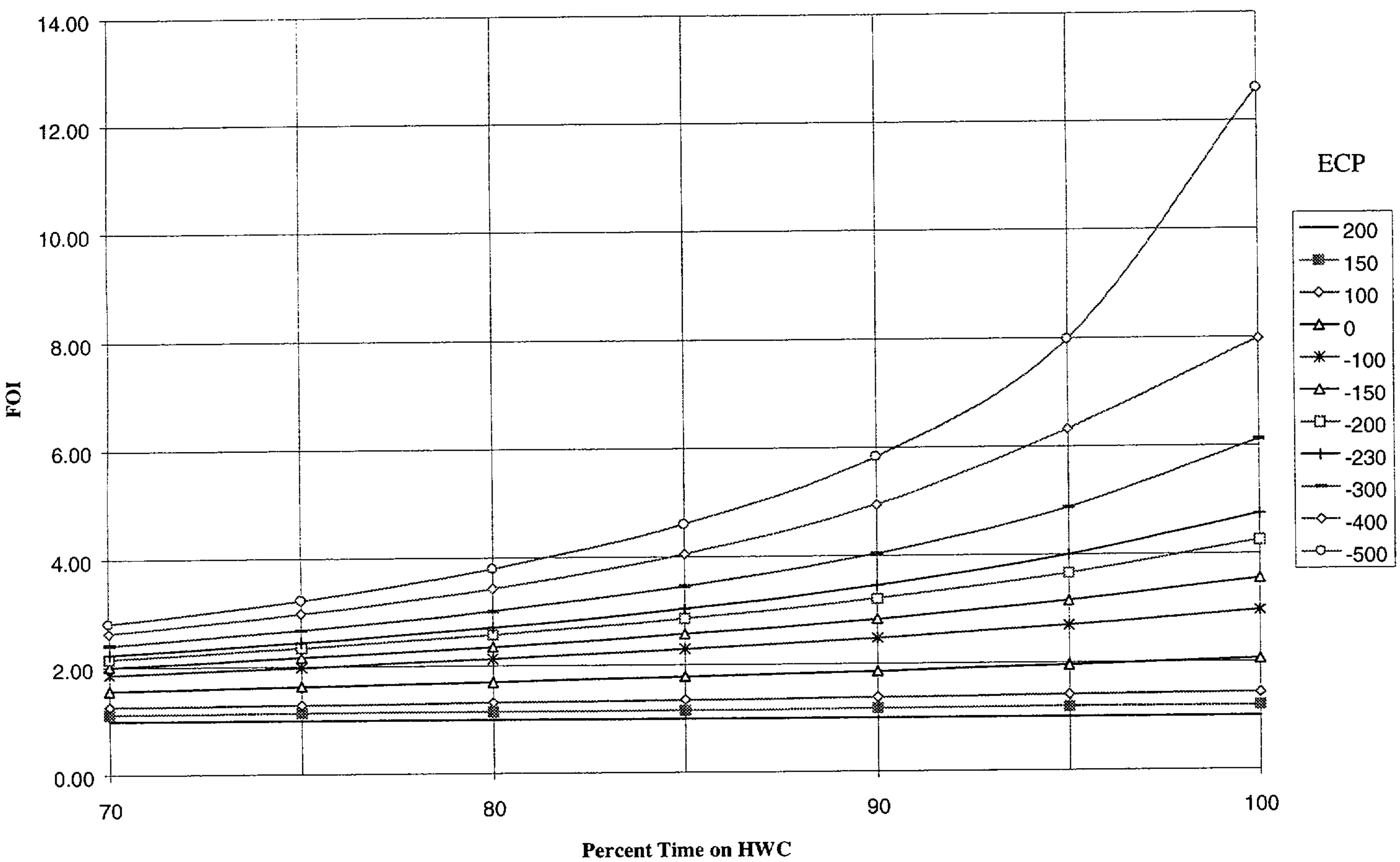

Figure 4-1. Plot of Stainless Steel Crack Growth Rate Factors of Improvement (FOI) based on HWC Availability as a Function of ECP

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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)

5.0 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.

5. Empirical crack growth models for stainless steel and nickel-base Alloy 182 weld metal indicate that a FOI of two reduction in crack growth rate is readily achievable with a HWC-M or NMCA availability of 70%.

Targets:
Nuclear Power

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