BWR Water Chemistry Guidelines – 2000 Revision

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ABSTRACT

Control of boiling water reactor (BWR) water chemistry increases plant availability by reducing intergranular stress corrosion cracking (IGSCC) in cooling system piping and reactor internals. These guidelines provide water chemistry recommendations for BWRs during all modes of operation. This revision of the 1996 guidelines incorporates new information that plant personnel can use to develop proactive plant-specific water chemistry programs that minimize IGSCC, fuel performance degradation and radiation build up.

EPRI FOREWORD

Intergranular stress corrosion cracking (IGSCC) can limit the service life of susceptible materials and components in BWR water environments. Discovery of IGSCC in the core shrouds of several plants indicates that cracking may be present in other reactor internal components. The importance of the role of the BWR environment in the IGSCC process has been recognized for some time. Laboratory studies have also shown that certain impurities in the water, such as sulfate and chloride, can accelerate initiation of IGSCC and promote high crack growth rates. The localized corrosion potential also influences the initiation and growth of IGSCC. Recognizing this, the BWR Water Chemistry Guidelines Committee and the Mitigation Committee of the BWR Vessel and Internals Program (BWRVIP) have issued these revised guidelines to establish a proactive position on water chemistry for mitigating IGSCC while maintaining fuel integrity and controlling radiation fields.

Hydrogen water chemistry (HWC) has been shown to be an effective method of mitigating IGSCC by reducing corrosion potential, though it has demonstrated side effects. As in the 1996 revision, the authoring committee recognized that site-specific chemistry control involves an optimization process. This revision continues to state that HWC should be incorporated into the station chemistry program, unless an engineering evaluation is performed which demonstrates that it is not cost-effective.

Specific changes to this document were made as noted below:

- Section 1 "Management Responsibilities" discusses the importance of good water chemistry control in obtaining inspection relief from NRC.

- Section 2 has been reformatted to be consistent with the equivalent section in BWRVIP-62 on inspection relief for core internals. This discussion provides the basis for the HWC recommendation, and the role of impurities on IGSCC, in the water chemistry limits contained in Section 4. Section 2 also separates the potential effects of coolant impurities by normal water chemistry (NWC) or HWC environments.

- Plant experience on noble metal application to increase the efficiency of hydrogen has become available since the last edition, and several more plants are planning to apply the process. Accordingly, noble metal considerations are discussed in each section of the document and the old appendix on NMCA has been deleted.

- Section 3 covers other factors, besides IGSCC, that are influenced by water chemistry. The discussion of the effect of HWC and zinc injection on radiation fields has been updated with the most recent plant data. The discussion on control of feedwater iron has been strengthened.

- The discussion of water chemistry effects on fuel integrity in Section 3 is mainly unchanged, but a brief discussion on recent fuel failures was added late in the guidelines preparation process. The Action Level 1 limit for feedwater copper has been reduced from 0.5 to 0.2 ppb, and diagnostic parameters added for feedwater and reactor water iron.

- Recent plant data on the effect of oxygen on flow-accelerated corrosion (FAC) has resulted in the Action Level 1 limit for dissolved oxygen in the feedwater being raised from a minimum of 15ppb to 30ppb.

- The recommendations for water chemistry control and diagnostic parameters in Section 4 now include separate tables for normal water chemistry and hydrogen water chemistry (including NMCA). Relaxation of the limits for chloride and sulfate is possible in the HWC cases.

- Recommended chemistry surveillance was reviewed and reduced, wherever appropriate, in support of the utility drive to reduce O&M costs (Section 5).

- A new appendix on the effects of impurity transients on crack growth rates is added, including examples of decision trees for evaluating actions to minimize the detrimental effects on stress corrosion cracking.

This guideline document replaces the *BWR Water Chemistry Guidelines - 1996 Revision - Normal and Hydrogen Water Chemistry Guidelines.*

C. J. Wood, Chairperson
BWR Water Chemistry Guidelines Committee

1

MANAGEMENT RESPONSIBILITIES

1.1 INTRODUCTION AND GUIDELINES OBJECTIVE

Water chemistry controls in BWRs can be applied to mitigate the corrosive environments inherent in BWR operation. This guideline document provides a framework for a BWR water chemistry program. It provides the technical bases for water chemistry controls, a series of chemistry control options and data evaluation techniques. Appendices are included to provide information to the user on how to determine which of the control options should be included in a site-specific chemistry control program. Hence, the objective of this document is to provide a framework for development of a plant-specific BWR chemistry control program; one that achieves the water chemistry control objectives noted in Section 3 as well as the utility objective to produce safe, reliable and economical electrical power.

This document has been cooperatively produced by a select industry committee of chemistry and materials specialists and the Mitigation Committee of the BWR Vessel and Internals Project (BWRVIP). It provides an approach to achieve protection of materials of construction while maintaining operational flexibility. In addition, this document provides a chemistry philosophy for materials protection that can be used by utilities to obtain relief from certain inspection requirements, as proposed by the BWRVIP. The chemistry program offered is based on research data and plant results that demonstrate its effectiveness.

The BWRVIP is working with the NRC on revision of IGSCC inspection frequencies for BWRs that have implemented hydrogen water chemistry or Noble Metal Chemical Application (NMCA). The revision will cover inspection of the piping welds within the scope of Generic Letter 88-01 (NUREG 0313) as well as vessel internals. A report providing the technical basis for inspection relief for BWR internals (BWRVIP-62) is being reviewed by the NRC and another report proposing revised inspection frequencies for piping welds will be submitted for NRC review in 1999. The NRC has indicated that operation in compliance with the EPRI Water Chemistry Guidelines is an important factor in deferring inspections. Compliance in cases such as this refers to Section 4.3 Guidelines Values for Control Parameters. The control parameters that affect IGSCC include ECP, conductivity, sulfate and chloride.

1.2 WATER CHEMISTRY MANAGEMENT PHILOSOPHY

Nuclear station management is charged with generating safe, reliable and low-cost electric power. Management is periodically faced with a choice of either keeping a unit available to produce power to meet short-term system demands or maintaining good control of chemistry to help assure the long-term integrity of the reactor and reactor coolant system, including fuel, balance-of-plant (BOP) and turbines. To effectively deal with these concerns, it is important that all levels of utility management understand that a successful chemistry program must ensure compliance with regulatory commitments and established industry guidelines for system/materials integrity, while meeting the economic demands of power generation. Management must understand that operation with off-normal chemistry may result in long-term loss of unit availability. Such losses can be minimized by limiting the magnitude and duration of off-normal chemistry. Utility management must support the chemistry guidelines both in principle and in detail to ensure their effectiveness. The goal of water chemistry control is to extend the operating life of the reactor and reactor coolant system, BOP components, and turbines while simultaneously controlling costs to retain continued economic viability of the nuclear power generation investment.

Boiling water reactor (BWR) components are susceptible to damage due to intergranular stress corrosion cracking (IGSCC) and other types of corrosion. Costs, including extended outages and increased radiation exposure, associated with the inspection and repair of IGSCC in recirculation piping and vessel internals have been significant; IGSCC of reactor internals can result in very high repair costs. In addition, damage is often detected by inspection, and discovery of cracking increases the inspection program, which adds additional inspection-related costs. Alternative chemistry regimes such as hydrogen water chemistry (HWC) and other alternatives (such as noble metal chemical application) are expected to provide opportunities for the mitigation of IGSCC of reactor internals. The chemistry program should be a plant-specific program based on factors such as design, condition, response to hydrogen, etc. In addition, water chemistry changes should also be evaluated for their potential impact on fuel integrity. Chemistry monitoring programs should be designed to provide early detection of fuel failures. Utility management should be sensitive to the operating costs and lifetime economic impact of all chemistry-related issues. Appendix A addresses a generic methodology for HWC cost evaluations and presents some case studies for application of the methodology.

The information presented in this section is based on observations that operating and maintenance philosophies with regard to chemistry can significantly affect major component life expectancy. The philosophy and policies discussed reflect the desirability of operating in a proactive rather than a reactive mode. The costs associated with maintaining water chemistry within these industry recommendations are likely to be less than those associated with the repair or replacement of reactor or reactor coolant system components or other major components and the outages associated with those efforts.

This section addresses general management responsibilities and is not intended to specify a management plan, organization, or specific responsibilities. Additional organizational and administrative guidelines are presented in *INPO Guidelines for Chemistry at Nuclear Power Stations, Rev. 2* (INPO 88-021, Rev. 2). Utility personnel are encouraged to combine the recommendations in this document with the INPO recommendations when developing/revising their site-specific programs.

1.3 GENERIC MANAGEMENT CONSIDERATIONS

This section discusses the considerations needed to carry out the water chemistry program effectively. Actions are identified without specifying responsibility for completing them. Utility-specific implementation policies and procedures should assign the responsibilities to specific positions within the organization. One major element of these guidelines is the need for every level of management to understand the importance of the action levels presented in Section 4 and their potential impact on, and benefits to, the utility. In addition, there is a need for management to support an effectiveness assessment approach similar to that discussed in Section 5.

An important ingredient of a successful management plan for water chemistry control is a set of specific written policies that implement these operating guidelines. Each policy should:

a. State the need for the policy

b. State the goals regarding water chemistry and station operation

c. Highlight corporate management support for the policy/procedure

d. Assign responsibility for:

- Preparation and approval of procedures to implement the policy
- Assessment of the effectiveness of chemistry control in minimizing system and component degradation
- Monitoring, analysis, and effectiveness evaluations of the chemistry program
- Surveillance and review functions
- Corrective actions

e. Establish the authority to:

- Carry out procedures
- Implement corrective actions
- Change the plant by modification or addition
- Complete economic reviews
- Resolve disagreements

Procedures implementing these policies normally are separate documents but should, when taken together, contain the level of detail necessary for personnel at all levels to understand and carry out their responsibilities.

Utility personnel responsible for plant design and modification of chemistry-related areas should:

a. Understand system design; materials of construction; the effect of chemistry on radiation buildup, radioactive water production, and fuel performance; and the effect of materials of construction on plant water chemistry

b. Ensure that the system design is reviewed by experienced plant operating personnel, vendors, and/or consultants, as appropriate

c. Be sensitive to operating costs and lifetime cost impact

d. Control the modification process and costs.

During the start-up (coolant > 200°F (93°C) and operating phase, the components and systems are particularly sensitive to water and steam chemistry/purity. Operating procedures should address:

a. Chemistry control limits and corrective action requirements

b. A plant-specific chemistry monitoring/surveillance program to assure that any chemistry excursion is quickly identified, commensurate with impacts, i.e. degree and time dependency

c. Detailed chemistry procedures containing action levels, specific responses to each action level, and corrective action notification and responsibilities

d. Quality control techniques that ensure on-line monitors and laboratory data are accurate

e. Standardized analytical procedures to ensure accurate laboratory results

f. Provisions for data review and assessment to monitor program implementation and to identify needed improvements.

1.4 TRAINING AND QUALIFICATION

A program for periodic (continuing) training of all personnel involved with water chemistry control should be established. This program should incorporate the latest information available from EPRI, other utilities, and the reactor and turbine vendors. Some indoctrination in the basics of the program should be considered for all employees who, by virtue of their job responsibilities, can affect water chemistry.

The training programs should be designed for the level and qualifications of personnel being trained. The following elements should be included:

a. A clear statement of the policy regarding water chemistry control, including clarification of the impact of this policy upon the various areas of responsibility

b. Identification of the impact that poor chemistry control has on major component performance, unit availability, and corporate economic performance

c. Techniques for recognizing unusual conditions and negative trends, particularly for the station chemists and laboratory technicians (Positive trends should also be recognized to determine why something improved. Potential corrective actions and their consequences should be thoroughly discussed.)

d. The interaction of system operations and chemistry.

Utility experts have also identified the importance of understanding the technical basis/rationale of the water chemistry program (See Excellence in Human Performance, INPO, September 1997). These experts suggest that the error rates associated with knowledge-based activities might be greater than skill or task-based activities due to lower training priorities. Thus, there is an underlying need for utility training programs to strengthen the fundamental knowledge of the chemistry staff with the concepts presented in this document.

1.5 SUMMARY

It is recognized that a specific program applicable to all plants cannot be defined in this document due to differences in design, materials, experience, management structure, and operating philosophy. However, the goal is to maximize the availability and operating life of major components and systems. To meet this goal, an effective corporate policy and water chemistry control program are essential and should be based upon the following:

- A recognition of the long-term benefits of, and need for, avoiding or minimizing corrosion degradation of major components including the fuel,

- Clear and unequivocal management support for operating procedures designed to avoid this degradation,

- Adequate resources of staff, equipment, funds, and organization to implement an effective chemistry control policy,

- An evaluation of the basis for each chemistry guideline and action level and specification of similar guidelines and action levels, as appropriate, for the specific plant,

- Management agreement at all levels, prior to implementing the program, on the actions to be taken in response to off-normal water chemistry and the methods for resolution of conflicts and unusual conditions not covered by the guidelines,

- Continuing review of plant and industry experience, research results, and revisions to the program, as appropriate,

- A recognition that alternate water chemistry regimes, if used, should not be a substitute for continued vigilance in adherence to the guidelines, and

- Minimizing radioactive waste generation and plant radiation levels.

2

TECHNICAL BASIS FOR WATER CHEMISTRY CONTROL OF IGSCC IN BOILING WATER REACTORS

2.1 HISTORY OF SCC IN BWRs

The original goal of BWR water chemistry specifications was primarily to control conductivity and chloride levels to prevent the occurrence of transgranular stress corrosion cracking (TGSCC) of stainless steels, a well-known degradation mechanism for this family of materials exposed to chlorinated environments. However, early testing techniques such as bent beams did not fully reveal the severity of the oxidizing nature of the BWR environment or the long incubation period for IGSCC initiation and subsequent growth in weld or furnace sensitized stainless steel. Also, the contribution of the high tensile residual stresses that could be produced by welding and grinding was not well understood. These factors, i.e., oxidizing environment and high tensile residual stresses, have led to a series of IGSCC events chronologically listed in Table 2-1 (2-1). Early observations of IGSCC were thought to be unique, and the overall generic implications of IGSCC in BWRs were not fully recognized until the late 1970s and early 1980s.

Since the recognition of IGSCC in BWR structural materials, a number of remedies have been qualified that address the materials, tensile stress and environmental aspects of this phenomenon (2-2). While this and previous versions of the BWR Water Chemistry Guidelines emphasize environmental IGSCC mitigation techniques, this revision includes the recent results of the BWRVIP program that developed a basis for inspection relief for BWR internals based strictly on environmental considerations (2-3).

2.1.1 IGSCC of Stainless Steel and Nickel-Based Alloy Components

IGSCC in BWRs was first observed in annealed stainless steel fuel cladding, due to continuous straining of the fuel (2-4), and also in furnace sensitized stainless steel, due to chloride impurities during construction and operation (2-5). Beginning in 1974, small diameter (4-10 inch [10 – 25 cm]) pipes constructed of annealed Type 304 stainless steel developed IGSCC in the heat affected zone (HAZ) of butt welds due to weld sensitization, in conjunction with the high weld tensile residual stresses found in small diameter pipe (2-6). Later, IGSCC in large diameter recirculation system piping was identified, leading to major expenses to inspect, repair and replace stainless steel piping in BWRs (2-7).

Laboratory testing had confirmed the relationship between IGSCC failure of specimens and exposure to simulated BWR oxidizing conditions. Early efforts at mitigation of the problem involved either residual tensile stress reduction in existing piping such as utilizing induction heating or mechanical stress improvement techniques or the replacement of the existing piping with Types 304NG and 316NG (Nuclear Grade) stainless steel. In 1988, the NRC issued NUREG 0313, Rev. 2, that recognized the mitigation methods used by the industry to address the pipe cracking issue (2-8).

Table 2-1: Evolution of SCC in the BWR (2-1)

EVENT	YEAR 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 Type 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	1990 – present

Nickel-base weld metal Alloy 182 is used extensively in the reactor internals of most BWRs to make the transition weld from the low alloy steel pressure vessel material to stainless steel components or in locations where wrought nickel-base Alloy 600 is utilized. IGSCC in Alloy 600 and Alloy 182 has been observed since the late 1970s in recirculation inlet nozzle safe ends (2-9). IGSCC in Alloy 182 weld butters on various nozzles has also occurred. Subsequent inspections of the shroud support access hole cover, a creviced vessel internal component made of Alloy 600 and 182, found IGSCC in plants with 6 to 16 on-line years, i.e., operating time at >0% power (2-1).

2.2 STRATEGY FOR MITIGATION OF INTERNALS CRACKING

Some of the previous IGSCC concerns in BWRs have largely been resolved by replacing the impacted materials with more IGSCC-resistant materials or by performing simple repairs. However, there is a limit to what can be achieved by replacement and repair. For example, repair/replacement of internals below the core is expensive and could lead to premature shutdown and decommissioning in the worst cases. An aggressive mitigation strategy will reduce the probability of escalating repair costs.

For many BWRs, the best-available initial strategy is likely to be to adopt HWC-M (1.0-2.0 ppm H_2 in feedwater) to protect components in the lower core region as soon as possible. This provides protection to plant components thought to be the most difficult to repair while minimizing the HWC side effects. Plant data should be used to optimize the hydrogen feed rates. The steps below outline this initial strategy:

1. Select target components and locations to be protected. This should include components in the lower core region.
2. Select ECP control point. A default value of -230 mV (SHE) is recommended.
3. Conduct a cost-benefit analysis of HWC to protect vessel internals and piping. This should include an evaluation of HWC side effects and the station's capacity to deal with these effects.
4. Select monitoring parameters. This should include ECP in the lower core region (Section 2.10.2) or alternative parameters (after bench marking with the plant's operating data) as a substitute for ECP (Section 2.10.3).
5. Initiate hydrogen injection in the feedwater.
6. Establish relationship between ECP at the target component, secondary parameter and the hydrogen addition rate.
7. Select a plant-specific hydrogen addition rate. For jet pump plants, this rate is expected to be in the range of 1-2 ppm to protect components in the lower core and lower plenum region, with low power density plants requiring more hydrogen than high power density plants.
8. Use a crack growth model consistent with available data to quantify the effects of off-hydrogen operation and conductivity transients.

For other BWRs, HWC-M may not be economically feasible and the implementation of NMCA will provide the IGSCC mitigation solution.

2.4 RECOMMENDATION

All utilities not currently using HWC-M should conduct an updated economic analysis. If the analysis indicates that moderate HWC or NMCA is cost-beneficial, it is recommended that they implement HWC-M or NMCA to protect components in the lower core and lower plenum region. However, as noted in Section 3, additional fuel technical issues need to be assessed with NMCA implementation.

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3

OTHER FACTORS INFLUENCED BY WATER CHEMISTRY

3.1 GOALS OF A BWR WATER CHEMISTRY PROGRAM

As discussed in Section 2, water chemistry is of critical importance to the operation and economic viability of BWRs. A successful water chemistry program must be designed to address the following goals:

- Minimize the incidence and growth of intergranular stress corrosion cracking (IGSCC),
- Minimize irradiation-assisted stress corrosion cracking (IASCC),
- Minimize plant radiation fields controllable by chemistry,
- Maintain fuel integrity by minimizing cladding corrosion, and
- Minimize flow-accelerated corrosion (FAC) in primary system and balance-of-plant (BOP) components.

The impact of water chemistry on IGSCC and IASCC was presented in Section 2. The chemistry control effects on radiation fields, fuel integrity and FAC are discussed in this section. It should be noted that water chemistry programs must also include surveillance and operating limits for other plant water systems, (e.g., service water, closed cooling water systems, etc.). These are out of the scope of this guidelines document and have traditionally been addressed elsewhere.

3.2 CHEMISTRY CONTROL EFFECTS ON RADIATION FIELDS

The main objective of radiation field control in a nuclear power plant is to maintain personnel exposures as low as reasonably achievable (ALARA). Startup, shutdown and operational chemistry controls, as well as other techniques like cobalt removal, surface preconditioning and chemical decontamination, can help minimize plant radiation fields. These techniques and their effects on radiation fields are summarized in the EPRI Radiation-Field Control Manual - 1997 Revision (3-1).

The ^{16}N ($t_{1/2}$ = 7.1 sec) activity is the primary source of radiation fields in the BWR coolant and steam systems during power operation. Because of its high-energy gamma rays, the radiation fields in the turbine building, plant environments and off site are dominated by the ^{16}N activity in the BWR steam. Hydrogen addition to the coolant can significantly increase the operating dose rate by increasing the ^{16}N concentration in the steam.

The major radiation source in the BWR for personnel exposure during shutdowns is activated corrosion products, mainly ^{60}Co ($t_{1/2}$ = 5.27 years), deposited on primary systems surfaces. Exposures are generally accumulated at high radiation field locations where maintenance work is frequently needed. Although improvement of maintenance equipment and procedures, reduction of maintenance requirements, increased hot-spot shielding, and control of contamination dispersion have significantly reduced total exposure, further reduction of radiation fields is a major goal in programs for minimizing occupational radiation exposure. In several plants, hydrogen addition to the coolant has significantly increased shutdown dose rates by redistributing in-core activated corrosion products to out-of-core regions. A further goal is therefore to minimize the effects of HWC on shutdown radiation fields.

3.3 CHEMISTRY CONTROL FOR FUEL INTEGRITY CONCERNS

Nuclear fuel is contained in Zircaloy-2 cladding that constitutes the first containment boundary for the highly radioactive species generated by the fission process. Therefore, the integrity of the cladding must be ensured. Zircaloy interacts with water, producing a surface layer of zirconium oxide and hydride platelets in the cladding. In LWRs, the zirconium oxide normally exists as a uniform layer. However, because of the oxidizing environment inside fuel channels due to radiolysis, a localized corrosion, called nodular corrosion, can also occur in BWRs. A nodular oxide can grow at a rate up to 10-100 times faster than the uniform oxide. The nodular corrosion can be controlled by optimization of the cladding alloy chemistry and processing history. Current Zircaloy-2 cladding generally possesses high resistance to nodular corrosion.

Zircaloy-2 cladding corrosion can also be impacted by crud deposition on the fuel rod surface. Soluble and particulate corrosion products of the system surfaces accumulate on fuel rods in BWRs in the form of oxide deposits. In general, crud deposition on the fuel rod surface starts at the location where nucleate boiling begins and reaches a peak at 20 to 40 inches (50 to 100 cm) above that point.

3.4 CHEMISTRY CONTROL FOR FLOW-ACCELERATED CORROSION CONCERNS

Flow-accelerated corrosion (FAC, also called flow-assisted corrosion and, misleadingly, erosion/corrosion) causes wall thinning of carbon steel piping, vessels, and components. The wall thinning results from dissolution of the normally protective oxide layer, (e.g., magnetite), that forms on the surface of carbon and low alloy steel when exposed to moving water or wet steam. The oxide layer reforms and the process continues. The problem is widespread in all types of conventional and nuclear power plants. Wall thinning rates as high as ~120 mpy (3 mm/year) have been observed. If the thinning is not detected in time, the reduced wall cannot withstand the internal pressure and other applied loads. The result can be either a leak or complete rupture.

The rate of wall loss (wear rate) of a given component is affected by the alloy composition, the pH at operating conditions, dissolved oxygen, fluid bulk velocity, component geometry and upstream influences, fluid temperature and steam quality.

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4

BWR WATER CHEMISTRY CONTROL RECOMMENDATIONS

4.1 INTRODUCTION

Recognizing the increasing urgency of corrective actions with increasing impurity concentrations, the following rationale was used for establishing water chemistry control parameters, recommended operating limits, and suggested monitoring frequencies:

- Ingress of impurities into the RCS should be kept to a practical and achievable minimum.
- The oxidizing power of the reactor water should be maintained below a value at which both laboratory and specific reactor experience demonstrates that sensitized austenitic stainless steels do not exhibit detectable rates of IGSCC.
- Action levels should be based on quantitative information about the effects of the chemistry variables on the corrosion behavior of RCS materials, fuel performance and radiation field buildup. In the absence of quantitative data, achievable action level values should be specified.
- Action levels should be variable if other chemistry initiatives that reduce the corrosion risks of water chemistry transients have been implemented.
- Recommended control, diagnostic, and confirmatory parameters should be reliably measurable at the levels specified using currently available equipment and procedures.
- Monitoring frequencies should be established with the recognition that utility resources should be devoted to high-priority work. Low-value work should be reduced or eliminated.
- The guidelines should be applicable for all plants, regardless of cooling water source.

The approach to minimizing the potential for IGSCC entails controlling both the ionic impurity content of the reactor water and the concentration of oxidizing radiolysis products.

4.2 DEFINITIONS OF TERMS USED IN GUIDELINES

To facilitate interpretation of the guidelines and recommendations presented in this section, several terms that are used repeatedly are defined in this section.

4.2.1 Plant Conditions

Three operational conditions are covered in the guidelines:

1. cold shutdown (≤200 °F [≤93 °C])
2. startup/hot standby (>200 °F [>93 °C]), ≤10% power), and
3. power operation (>10% power).

A modified definition of these conditions should be considered if conformance to Technical Specification definitions is desired. For example, some plant Technical Specifications incorporate 212 °F (100 °C) bulk coolant temperature to define plant conditions and operational requirements. For these plants, it might be desirable to change the 200 °F (93 °C) temperature used in the above definitions to 212 °F (100 °C) to be consistent. In addition, the power level above which hydrogen additions are made may be influenced by technical specification considerations as well as by plant design.

4.2.2 Parameter Values

Values are specified in the guidelines for most water chemistry parameters. These values are defined as follows.

Action Level 1 Value. The value of a parameter beyond which data or engineering judgment indicates that long-term system reliability may be threatened, thereby warranting an improvement of operating practices.

Actions if a parameter exceeds the Action Level 1 value:

(a) Restore the parameter to the Action Level 1 value as soon as practicable.

(b) If not restored within 96 hours, perform a review to assess the impact on long-term system reliability. Identify and evaluate corrective actions. Develop and obtain management approval of a written plan and schedule to implement corrective actions, if necessary.

Each plant should formalize a management awareness program for prolonged off-normal water chemistry conditions. This should include a mechanism for informing appropriate levels of management of the existence of the condition, the implications, and the possible corrective measures over the short and long term.

Action Level 2 Value. The Action Level 2 value of a parameter represents the range outside of which data or engineering judgment indicate that significant degradation of the system may occur in the short term, thereby warranting a prompt correction of the abnormal condition.

Actions if a parameter exceeds the Action Level 2 value:

(a) As soon as practicable, corrective action shall be initiated to reduce the parameter below the Action Level 2 value.

(b) If the parameter has not been reduced below the Action Level 2 value within 24 hours, an orderly unit shutdown shall be initiated and the plant shall be brought to cold shutdown as rapidly as operating conditions permit. In some cases, it may be more prudent to continue power operation if this results in minimized degradation of components during the period of elevated parameter concentrations. If such an approach is adopted, an engineering evaluation shall be performed to document how it is expected to result in acceptable degradation to the reactor materials.

(c) If it is foreseeable that the parameter will be below the Action Level 2 value within the time period required to achieve an orderly shutdown, power operation can be maintained.

(d) Following a unit shutdown caused by exceeding an Action Level 2 value, a review of the incident shall be performed and appropriate corrective measures taken before the unit is restarted.

Action Level 3 Value. The Action Level 3 value of a parameter represents the range outside of which data or engineering judgment indicates that it is inadvisable to continue to operate the plant. In a resin ingress scenario, it may be more prudent to maintain power operation if this results in minimized degradation of components due to elevated sulfate concentrations. If such an approach is adopted, an engineering evaluation shall be performed to document how it is expected to result in acceptable degradation to the reactor materials. This evaluation is likely to be case- and site-specific and should be performed during the chemistry program optimization phase rather than following an ingress incident. The recommended responses to exceeding Action Level 3 values are:

(a) Immediately initiate an orderly unit shutdown. (It should be recognized that it may take as long as four hours to identify the cause of the incident.)

(b) Reduce the parameter to below the Action Level 3 value as quickly as possible.

(c) Reduce coolant temperature to ≤200 °F (≤93 °C) unless it is foreseeable that the parameter will be below the Action Level 2 value within the time period required to achieve <200 °F (<93 °C).

Developing Plant-Specific Action Responses: It is recognized that there are a variety of circumstances that may result in exceeding chemistry action levels and that the responses for many of these may not be identical.

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DATA EVALUATION/MONITORING

The primary purposes of this section are to identify data evaluation methodologies and highlight the information available regarding monitoring methods and issues. The techniques that can be considered for evaluating the effectiveness of the water chemistry control program are also reviewed in this section of the guidelines.

5.1 DATA COLLECTION AND TRENDING METHODOLOGIES

Data should be promptly recorded in a format that is easily interpreted and retrievable. Data also must be promptly interpreted by comparison against clearly established and understood criteria. The interpretation must be made in a timely manner at an appropriate managerial or technical level to assess the need for and to implement necessary corrective actions. Early identification of adverse chemistry trends will minimize the development of conditions that require a power reduction or shutdown based on guideline action levels.

Effectively all BWRs utilize computer databases for storage and retrieval of chemistry data. Several BWRs also employ on-line data acquisition systems whereby data from process chemistry instruments are automatically entered into the chemistry database at a specified frequency. Some sites have interfaced the chemistry database with the plant process computer to provide direct access to reactor power, process flows and temperatures. The frequency of database entry depends on the methodology of data entry. Manual data collection and entry have obvious manpower time limitations. With on-line data acquisition, this limitation is not present.

5.2 MONITORING APPROACHES

5.2.1 Water Chemistry

Methodologies appropriate for measuring key BWR chemistry parameters are summarized. Procedures other than those identified may provide similar accuracy and sensitivity levels.

5.2.2 Electrochemical Corrosion Potential (ECP)

Early measurements of the chemical makeup of the NWC BWR environment showed that it was characterized by the presence of approximately 200 ppb O_2 and sub-stoichiometric 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 from 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. Model calculations typically predict hydrogen peroxide (H_2O_2) concentrations of 200 to 400 ppb.

The corrosion potential or the more commonly called electrochemical corrosion potential (ECP) is a measure, under certain fixed conditions, of the thermodynamic tendency for a material to undergo an electrochemical, i.e., corrosion, reaction. ECP quantifies the oxidizing power of a solution in contact with a 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. Iron/iron oxide (Fe/Fe_3O_4) and silver/silver chloride (Ag/AgCl) electrodes can be used over the entire range of water chemistries (NWC to HWC). From the measured value ΔV_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:

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

5.3 ECP MONITORING LOCATION SELECTION

The BWR typically operates with pure water with conductivity near 0.1 μS/cm. The continuous deposition of neutron and gamma radiation into the coolant coupled with the boiling in the core results in a steady state concentration of O_2, H_2 and H_2O_2 that is unique to each of the various locations inside the BWR. Because the ECP of BWR structural materials is very sensitive to the concentration of O_2, H_2 and H_2O_2, different locations will have different ECPs. This is especially true for BWRs operating with HWC to establish the HWC ECP guideline value of –230 mV(SHE) at key locations. Thus, the location of the ECP monitors within the BWR is of great importance, with the goal being to place the reference electrode as close as possible to the component(s) that is thought to require the highest feedwater hydrogen injection rate to reach the ECP guideline value. Unfortunately, there are only a few locations that are amenable for locating a reference electrode that are practical for measuring ECP within the BWR.

5.4 ALTERNATE ECP ESTIMATION TECHNIQUES

This section summarizes the methods that are available to demonstrate that HWC is being effectively implemented, especially when the in-reactor ECP measurements discussed in Section 5.3 are not available. 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) are 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. 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". 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.

5.5 FACTOR OF IMPROVEMENT (Calculational Basis)

The BWRVIP model discussed in Section 2 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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