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Boric Acid Corrosion:
Revision to BAC Guidebook

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BAC Guidebook Rev. 2

Topics

- Background, purpose, and scope of Guidebook (Section 1)
- Industry experience with leakage of borated water and the resultant corrosion (Section 2)
- Mechanisms by which borated water corrodes carbon and low-alloy steel materials (Section 3)
- Results of boric acid corrosion testing (Section 4)
- Related industry programs & documentation (Sections 5-9)
  - Regulatory bases
  - Detection of borated water leakage
  - Prevention of leakage and degradation
  - Justification for continued operation (JCOs) with degraded parts or ongoing leakage
  - Boric Acid Corrosion Control (BACC)

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Status

- Rev. 2 Guidebook will be issued in 2012
  - Industry review of draft beginning in 1st quarter of 2012
  - Updates plant experience, BAC test summaries, and conclusions regarding BAC mechanisms and rates based on developments since 2000
  - Understanding of effect of oxygen on BAC rate revised based on testing since 2003 (for low pH, the effect of oxygen is modest)
  - Also updates summaries of industry guidance on related topics

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BAC Guidebook Rev. 2: Section 1 Introduction

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Background

- There is little concern with corrosion inside the primary and secondary systems exposed to borated water since the boric acid and oxygen concentrations in these systems are low, the pH is controlled at mildly alkaline conditions
  - Corrosion rates are typically 0.001 in/yr or less
- However, borated water leaks (through gasketed joints, valve packing, stress corrosion cracks, etc.) can lead to significant corrosion problems due to boric acid concentration as the water boils off or evaporates, and oxygenation of the resulting solution takes place
  - These factors can increase the corrosion rate of exposed carbon or low alloy steel from <0.001 in/yr to as high as 10 in/yr

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Background (continued)

- Numerous BAC incidents have occurred over the years
  - Range of severity from minor corrosion of parts to major incidents involving plant shutdowns and significant loss of material on major components
- Three key examples highlight potential for significant consequences:
  - BAC of reactor coolant pump studs (7) at one CE-designed PWR in 1980
    - Diameters of worst case studs reduced from original 3.5 inches to 1.0–1.5 inches
  - Corrosion of high pressure safety injection (HPI) nozzle at one B&W-designed PWR in 1986
    - Corrosion extending as far as 2/3 through nozzle wall thickness traced to leakage from HPI isolation valve located ~8 feet above corroded area (valve had operated with known leak of <0.1 gpm for at least 5 months prior to discovery of corrosion)
  - Discovery of cavity in reactor vessel head (RVH) at another B&W-designed PWR in 2002
    - Cavity extended completely through the low alloy steel vessel head (only stainless steel cladding maintained pressure boundary)
    - Cavity determined to have been caused by BAC mainly over a period of about six years resulting from leakage through a PWSCC crack in an Alloy 600 CRDM nozzle

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Background (continued)

- Partially due to the first two BAC incidents described above, NRC issued Generic Letter 88-05, *Boric Acid Corrosion of Carbon Steel Reactor Pressure Boundary Components in PWR Plants*
  - Required that utilities develop and implement programs to identify leaks and take corrective action to prevent recurrence
  - All US PWRs have developed programs that respond to this letter
- Subsequent to the 2002 RVH BAC event, the industry and NRC have taken several actions to strengthen controls of boric acid corrosion
  - US industry committed via NEI 03-08, *Guideline for the Management of Materials Issues*, to comply with a number of documents, including WCAP-15988-NP, *Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors*, Revision 1, 2005
  - EPRI and NRC/ANL performed additional testing and analysis to better determine the factors that control boric acid corrosion rates

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Purpose of Guidebook

- Provide utilities with practical information to:
  - Support BAC control programs
  - Assess whether components can be left in service with continuing leakage or degradation
- Main phases of guidebook development:
  - 1995 Original BAC Guidebook (EPRI TR-104748)
  - 1996-1998 Performance of BAC screening tests and prototypical joint tests by EPRI
  - 2000-2001 Preparation of Revision 1 of the BAC Guidebook (EPRI 1000975)
  - 2011-2012 Preparation of Revision 2 of the BAC Guidebook to reflect test results developed by MRP and NRC/ANL subsequent to BAC cavity in reactor vessel top head in 2002

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Scope of Guidebook

- BAC is general corrosion caused by exposure to borated water of carbon and low alloy steel pressure boundary and other components in the primary system within containment
- Borated water sources considered:
  - Leakage of reactor coolant during operation through mechanical joints or primary water stress corrosion cracks in Alloy 600/82/182 components
  - Water from refueling activities
- Guidebook also presents available data on BAC rates of other materials used in the reactor building and the balance of plant that are potentially exposed to borated water (e.g., stainless steels, copper alloys, etc.)
- Boric acid corrosion of containment vessel liners, concrete, and rebar is not within the scope of the guidebook
- Guidebook does not address stress corrosion cracking (such as outer diameter SCC of sensitized and non-sensitized stainless steel components) as a consequence of exposure to borated water leaks (but does consider SCC as a potential initiator of leaks leading to BAC)

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Guidebook Table of Contents

- Section 1: Introduction
- Section 2: Industry Experience
- Section 3: Boric Acid Corrosion Mechanisms
- Section 4: Boric Acid Corrosion Tests
- Section 5: Regulatory Bases
- Section 6: Detecting Leakage
- Section 7: Preventing Leakage and Degradation
- Section 8: Continued Operation with Leakage and / or Degradation
- Section 9: Boric Acid Corrosion Control Programs
- Section 10: References
- Appendix A: Boric Acid Corrosion Test Data Summaries
- Appendix B: Reported Incidents of Boric Acid Corrosion
- Appendix C: Example Analyses

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Use of Guidebook

- The BAC guidebook is a key reference to WCAP-15988-NP, Rev. 1, *Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors*, February 2005
- WCAP-15988-NP, Rev. 1 requires that each PWR utility in the US have a Boric Acid Corrosion Control Program (BACCP) that addresses 11 specific elements
- The generic guidance of WCAP-15988-NP, Rev. 1 is considered "good practice" as defined by the NEI 03-08 implementation protocol

Revision 2 to WCAP-15988 is in preparation and will be issued this year

BAC Guidebook Rev. 2: Section 2 Industry Experience

BAC Guidebook Rev. 2

Industry Experience – Overview

- Section 2 documents industry experience with corrosion of carbon and low alloy steel (C&LAS) pressure boundary parts caused by leakage of borated water
  - Occurrence of leaks without associated corrosion damage of C&LAS parts also addressed
  - Damage to non-C&LAS pressure boundary materials and parts also reviewed to a limited extent
- Section 2 presents summary results – detailed tabulation of industry experience is in Appendix B "Reported Incidents of Boric Acid Corrosion"
- Focus of Section 2 in Rev. 1 was on leaks at sealed joints such as gasketed joints. In Rev. 2 focus also includes leaks caused by PWSCC

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Industry Experience – Database of Experience

- Database of industry experience started with database developed for Rev. 1 of Guidebook
  - Database updated by review of documents from 2000 and later of the following types:
    - LERs filed in NRC's ADAMS database
    - NRC documents such as information notices, bulletins, generic letters, and orders
    - EPRI reports and conference documents
    - Other technical literature
  - Database mainly limited to items reported publically
    - Covers all important events

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Industry Experience – Key Experience Since Revision 1

- Corrosion of C&LAS due to leaks caused by PWSCC
  - 2002 reactor vessel head (RVH) cavity event was the major event of this type
  - No structurally significant cases of corrosion of C&LAS pressure boundary parts since this 2002 event
- Corrosion of C&LAS due to leaks at sealed joints
  - No structurally significant cases of corrosion of C&LAS pressure boundary parts such as bolting since about 2000

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Industry Experience – Review of INPO Databases

- INPO databases contain data that are not publically available
  - Performed to ensure that no significant boric acid induced corrosion events were missed
  - Many cases of small leaks caused by PWSCC and at sealed joints
  - Very few cases of measurable corrosion of C&LAS pressure boundary parts
  - Significant cases are covered in publically available documents – listed in Appendix B of Guidebook Rev. 2

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Industry Experience – Additional Reviews

- Corrosion and damage to other parts
  - Electrical and control components
  - HVAC and air sampling components
  - Component supports
  - Other parts such as valve hard facing, pump casing at cracks in cladding
- Refueling cavity leakage and corrosion damage to containment liners
- Boric acid can be spread throughout containment building by HVAC
  - Need to limit leakage into containment

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Industry Experience – Conclusions

- Overall Experience
  - All leakage should be treated seriously and potential direct and indirect consequences evaluated
  - Components that are potential sources of leakage should be identified and evaluated to determine the possible consequences, and changes made as appropriate to prevent leakage or minimize consequences
- Recent Field Experience
  - Experience since 2003 indicates that current programs are preventing occurrence of significant corrosion damage to C&LAS pressure boundary parts

BAC Guidebook Rev. 2: Section 3 Boric Acid Corrosion Mechanisms

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BAC Mechanisms – Overview

- Section 3 covers the mechanistic understanding of BAC processes and the factors that affect corrosion rates
- Includes effect on wastage of the following based on standard corrosion science concepts (discussed in following slides):
  - Oxygen
  - Temperature
  - pH
  - Flow
- Effects of other factors (e.g., impurities, geometry, galvanic coupling) are discussed in a qualitative manner in the guidebook

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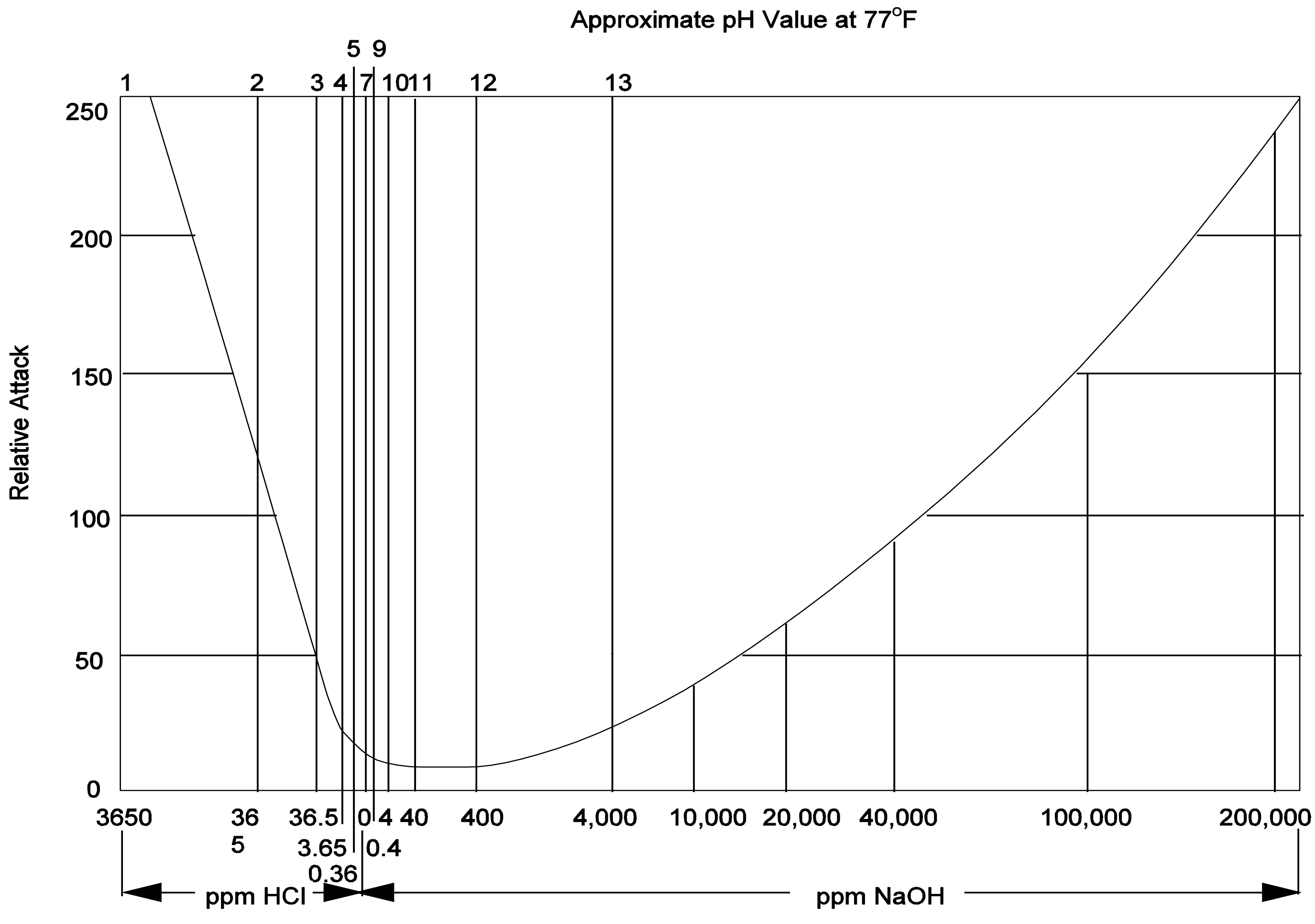
BAC Mechanisms – Effect of pH

- Corrosion of iron is generally low for 5 < pH < 13
- High BAC rates are associated with low pH



Typical Effect of pH on Corrosion Rate of Iron

Source: *Boric Acid Corrosion of Carbon and Low Alloy Steel Pressure-Boundary Components in PWRs*, EPRI, Palo Alto, CA: 1988. NP-5985.

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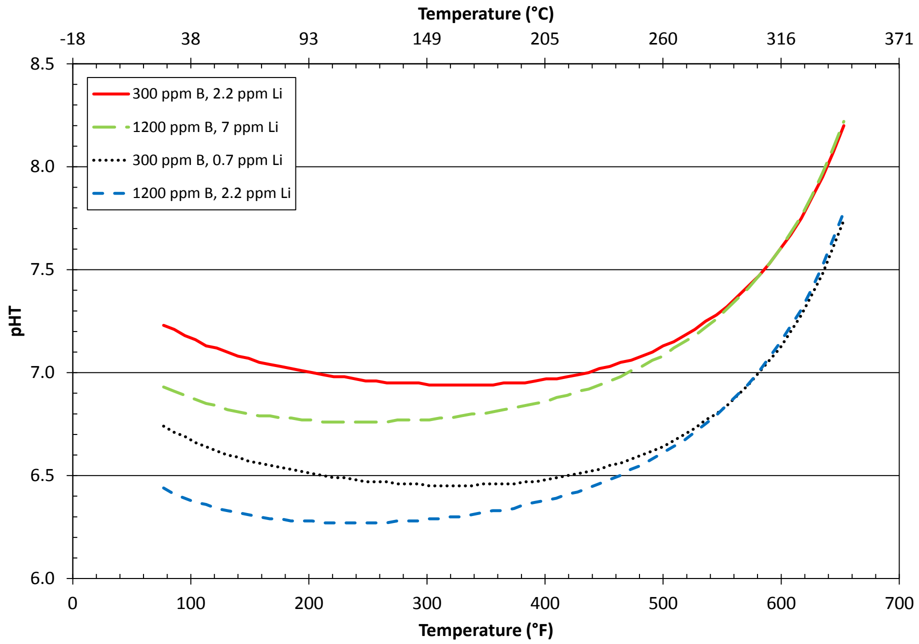
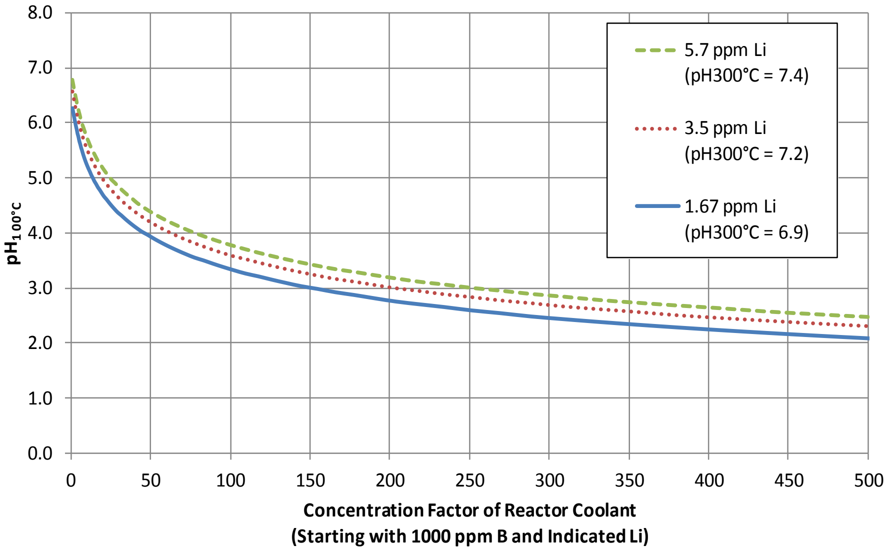
BAC Mechanisms – Temperature and Concentration Effects on pH

Constant chemistry gives lower pH values just from cooling



Concentration due to boiling also lowers the pH



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BAC Mechanisms – Overall Effect of Temperature

- Highest rates are generally around 212°F

- Thermal activation → higher rates at higher temperatures
- Moderate evaporation → lower pH → higher rates
- After dryout → essentially no corrosion
- Lower oxygen solubility at higher temperature → lower rates
- Higher temperatures → boric acid is weaker → less acidic → lower rates
- Higher temperatures → boric acid volatility → less acidic → lower rates

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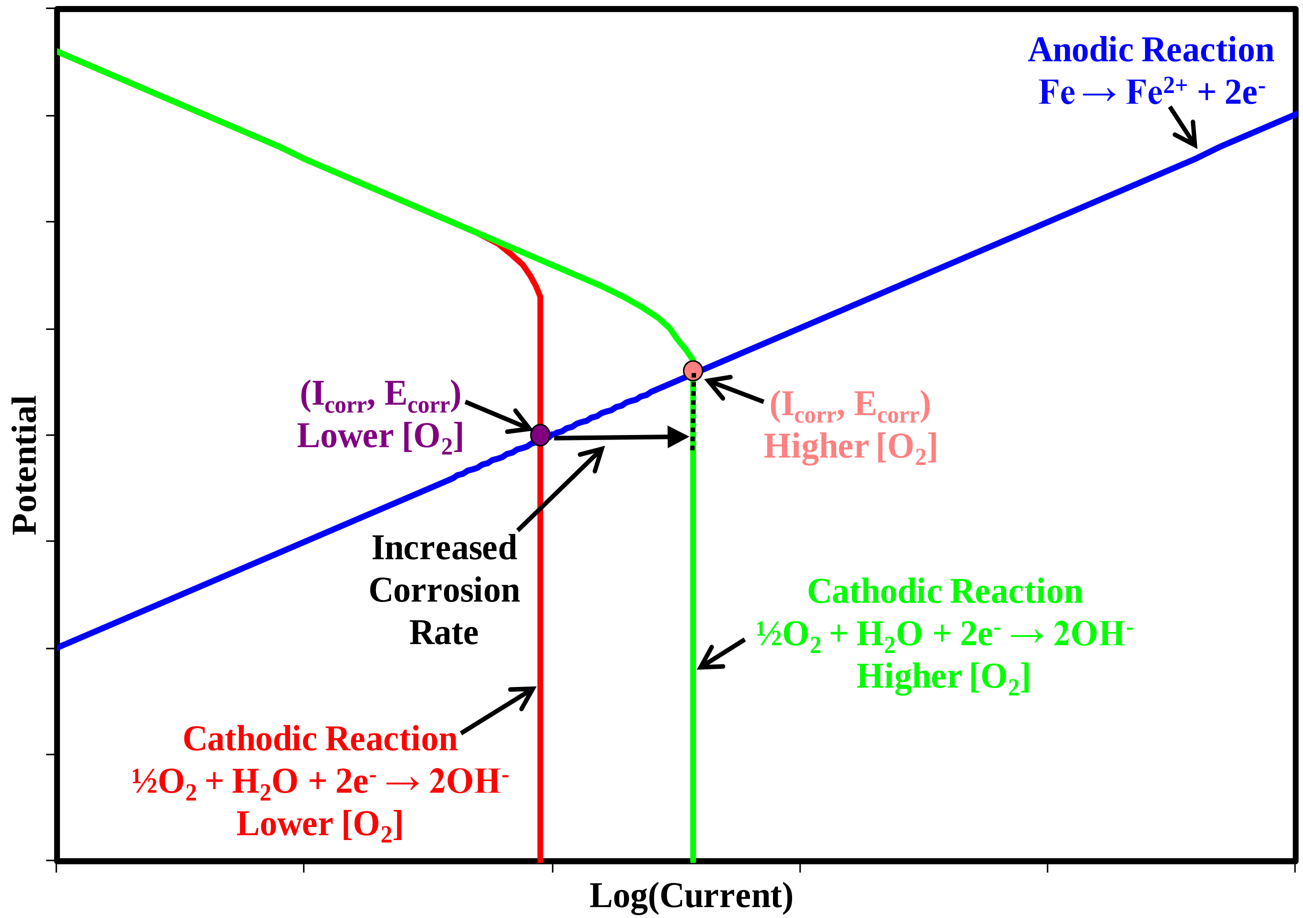
BAC Mechanisms – Effect of Oxygen

- No passivation, so oxygen expected to increase corrosion rates



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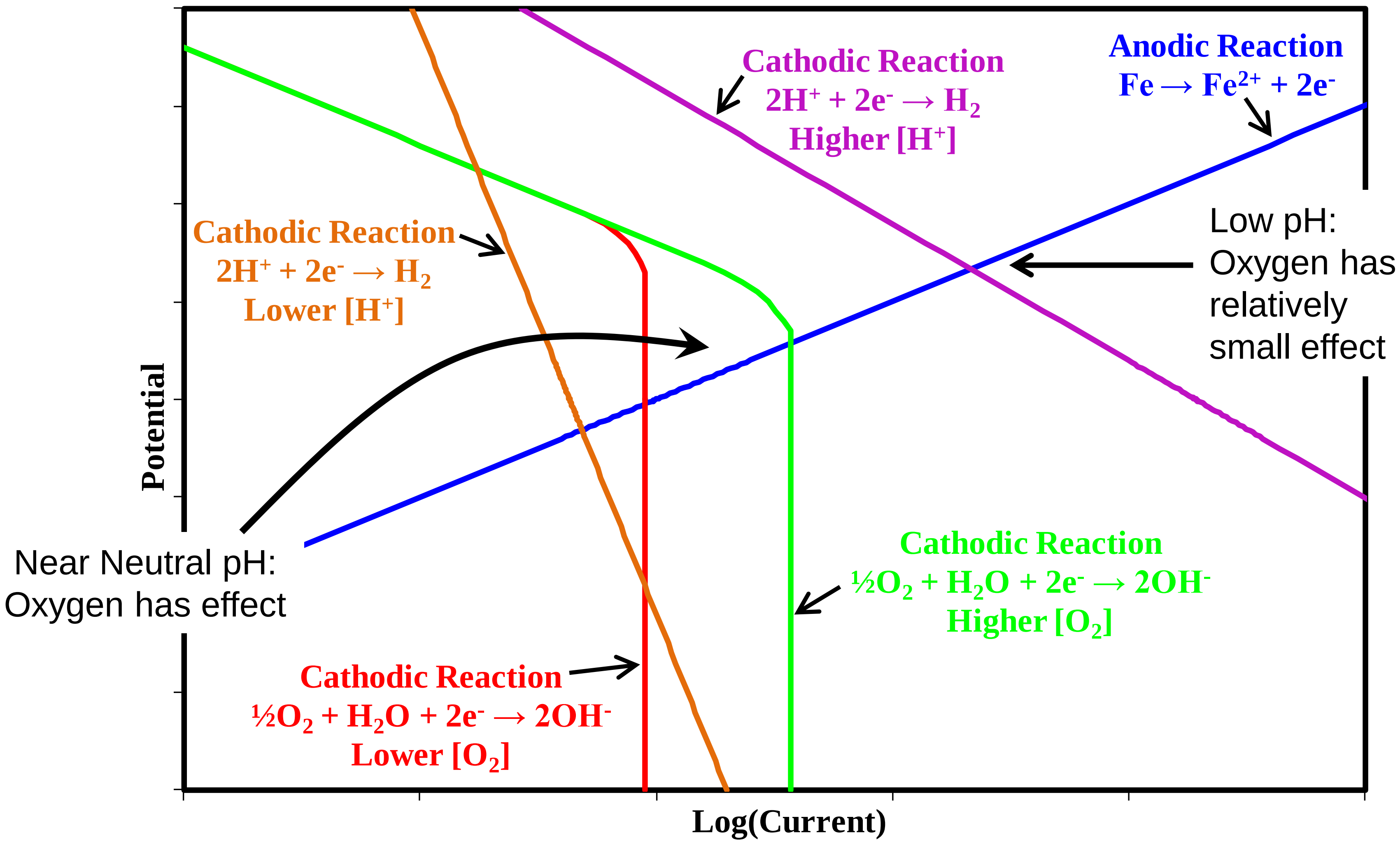
BAC Mechanisms – Relative Effects of Oxygen and pH



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BAC Mechanisms – Flow Effect

- Impingement by primary steam or droplets on hot metal surfaces can lead to high corrosion rates due to:
  - Refreshing corroding solution
  - Cooling of surfaces
  - Mechanical effects
  - Concentration of solution – changes in pH
  - Prevents dryout

BAC Guidebook Rev. 2: Section 4
Boric Acid Corrosion Tests

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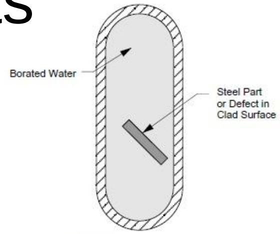
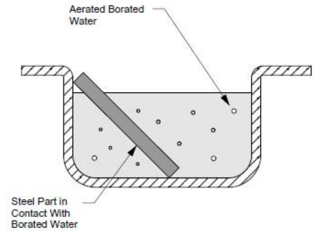
BAC Tests – Background

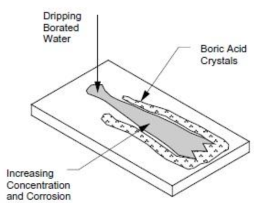
- Section 4 of the BAC GB describes test programs conducted to quantify corrosion rates of relevant materials in simulated primary water environments
- Tests are primarily divided into 5 simulated scenarios
  - Immersion of carbon steel in deaerated borated water
  - Immersion of carbon steel in aerated borated water
  - Dripping of borated water onto hot carbon steel surfaces
  - Impingement of borated water onto hot carbon steel surfaces
  - Leakage of borated water into a tight crevice (nozzle applications)



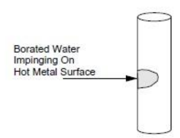
Immersion in Deaerated Water



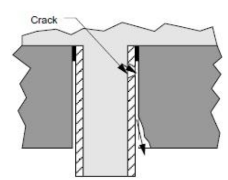
Immersion in Aerated Water



Dripping onto Hot Metal Surfaces



Impingement onto Hot Metal Surfaces



Leakage into Annular Gap

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BAC Tests – Timeline since Revision 1 of BAC Guidebook

- 2002 RVH cavity detected at one PWR

- 2004-2005 ANL completes a series of tests to help identify the cause of the 2002 RVH cavity
  - Focus on environmental conditions roughly corresponding to postulated phases of the 2002 RVH wastage

- 2005-2010 EPRI conducts BAC test program (Tasks 1–4)
  - To confirm assumptions of wastage models that form part of the technical basis for current periodic visual and surface/volumetric examinations to ensure structural integrity and maintain nuclear safety

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BAC Tests – Updates to GB Conclusions

- Immersion of Carbon Steel in Deaerated Borated Water
  - New test data show that oxygen was not the key driving factor in the results of other deaerated immersion tests previously discussed as part of revisions 0 or 1 of the BAC GB
  - Good correlation between corrosion rate and pH_T was obtained during MRP Task 3, with lower pH_T solutions resulting in higher corrosion rates
  - Corrosion rates for immersion in deaerated, dilute boric acid solutions (<3,000 ppm boron) peak near 212°F but are bounded by about 0.01 in/yr regardless of temperature
  - Moderate (~0.1 in/yr) to high (>1 in/yr) corrosion rates can be obtained during immersion in deaerated, concentrated boric acid solutions (i.e., >9,000 ppm boron) over a wide range of temperature depending on the B concentration, Li:B ratio of the solution, and moisture content of boric acid powder (as applicable)

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BAC Tests – Updates to GB Conclusions (Continued)

- Immersion of Carbon Steel in Aerated Borated Water
  - Corrosion rates for cases involving immersion in aerated borated water were observed to span a similar range to those under deaerated conditions illustrating the fact that the availability of oxygen is not as important as originally thought in earlier versions of this guidebook
  - Similar trends of generally increasing corrosion with concentration and temperature (up to about 212°F) were observed for aerated conditions as for deaerated conditions
  - Above 212°F, effects of concentration and temperature become somewhat competing with higher concentrations generally leading to higher corrosion rates, and higher temperature leading to lower corrosion rates

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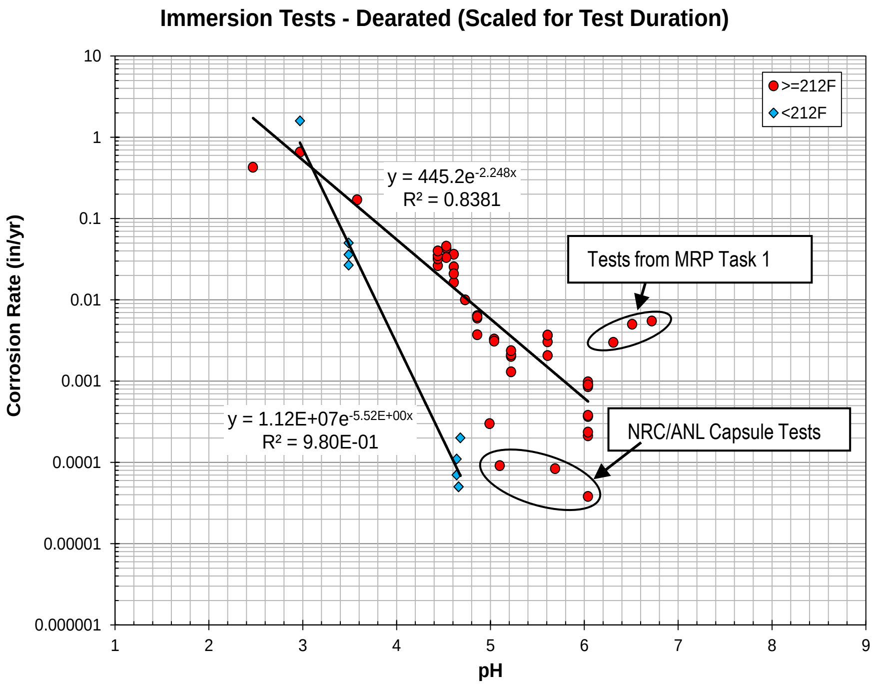
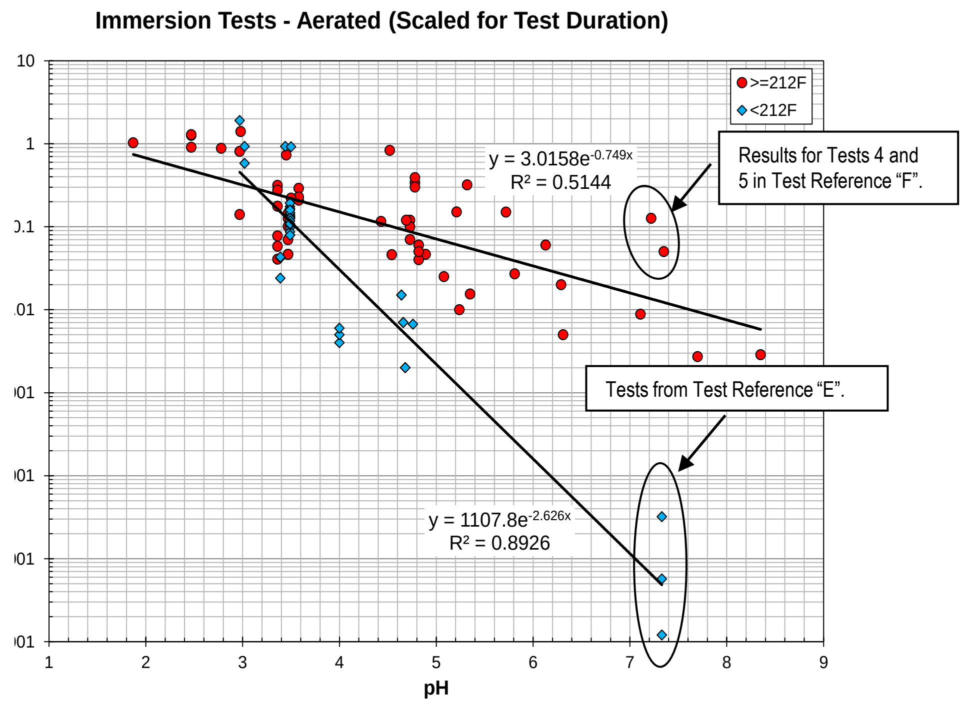
BAC Tests – Updates to GB Conclusions (Continued)

- Immersion of Carbon Steel in Borated Water
  - Reviewed available data and calculated pH_T (using MULTEQ) for all immersion tests
  - The conclusions in Task 3 (key wastage factor is pH_T) were applicable to the full set of immersion data in the Guidebook
  - Linear corrosion rates were adjusted to account for observed bias of increased rates for shorter duration tests (plotting data on common basis)





Effect of pH_T and Temperature on the Corrosion Rate of Low alloy Steel (Adjusted for Test Duration)

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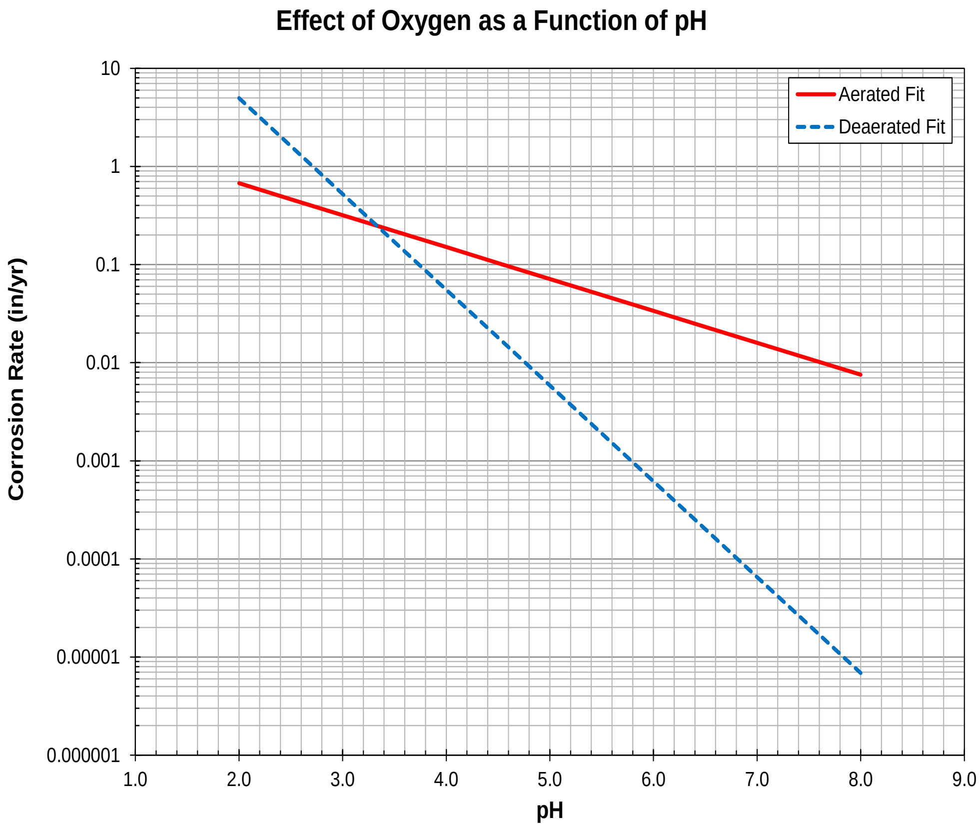
BAC Tests – Updates to GB Conclusions (Continued)

- Immersion of Carbon Steel in Borated Water
  - At high pH conditions, the presence of oxygen is important in estimating corrosion rates
  - At low pH conditions (applicable to concentrated low temperature boric acid solutions), the role oxygen is a secondary factor when estimating corrosion rates



Comparison of Fits to High Temperature (≥212°F) Aerated and Deaerated Data Demonstrating Effect of Oxygen as a Function of pH_T

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BAC Tests – Updates to GB Conclusions (Continued)

- Dripping of Borated Water onto Hot Carbon Steel Surfaces
  - The main problem regarding borated water dripping on heated metal surfaces is the potential lowering of the local metal temperature to a level at which significant concentration of the borated water can take place without significant volatilization of the boric acid
  - This scenario typically results in concentrated boric acid (low pH_T) near 212–220°F in contact with the heated metal surface
  - If the metal surfaces are sufficiently heated and the leakage rate sufficiently low, the solution can boil off quickly leaving dry boric acid crystals that result in essentially no corrosion
  - If the heating is insufficient or the leak rate too great, the conditions do not support significant concentration of the solution and lower corrosion rates are expected

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BAC Tests – Updates to GB Conclusions (Continued)

- Impingement of borated water onto hot carbon steel surfaces
  - If borated water impinges on hot metal surfaces, corrosion rates can be high due to the combination of high concentration, local metal temperatures near the boiling point of the borated water, and some mechanical effects due to flow impingement
  - Conclusions unchanged from Revision 1 of guidebook but interpretation of results and the driving factors updated in light of recent test data (i.e., increased role of local pH_T, less emphasis on the role of oxygen)

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BAC Tests – Updates to GB Conclusions (Continued)

- Leakage of Borated Water into a Tight Crevice (Nozzle Applications)
  - Conclusions in the guidebook relating wastage rate with leak rate are primarily based on the observations of the Task 4 testing since these tests represent what is considered to be the most prototypic conditions (e.g., thermal-hydraulic boundary conditions) available of leaking nozzles
  - Task 4 results suggest that under prototypic RPV head thermal boundary conditions, leak rates on the order of 0.001 gpm do not result in structurally significant wastage for timescales of interest
  - Higher leak rates can lead to corrosion rates exceeding 1 in/yr depending on the nozzle geometry (CRDM, BMN, etc.) and location (top head, bottom head, etc.)
  - Resulting wastage patterns are dependent on the combined effects of local pH_T and the flow pattern within the annulus
  - Majority of damage shown to be typically located within the annulus but the mockup tests support the conclusion that a structurally significant subsurface cavity would be preceded by visual evidence (as boric acid and / or corrosion products at or near the annulus exit)

BAC Guidebook Rev. 2:
Regulatory Bases (Section 5)
Detecting Leakage (Section 6)
Preventing Leakage and Degradation (Section 7)
Continued Operation with Leakage and/or Degradation (Section 8)
Boric Acid Corrosion Control (Section 9)

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Regulatory Bases

- Regulatory bases pertaining to leakage of borated water and possible resultant corrosion
  - Federal and NRC requirements
  - ASME Boiler and Pressure Vessel Code requirements
  - Industry Commitments
- Federal/NRC requirements
  - Design criteria in 10 CFR 50 Appendix A
  - Related and supporting information in Information Notices and NUREG reports
  - Requirements in bulletins, generic letters, orders, and 10 CFR 50.55a

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Regulatory Bases (continued)

- ASME requirements are mainly in Section XI and related Code Cases, and specify required inspections and repairs
- Industry commitments are in NEI 03-08 and invoke industry documents, including WCAP-15988-NP, Rev. 1, *Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors*
- Common themes of all requirements:
  - Closures should be designed, fabricated and maintained to have low risks of leakage and rupture
  - Programs must be in place to detect and correct leakage before significant damage occurs

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Detecting Leakage

- Describes regulatory and Technical Specification (TS) leakage detection requirements
- Summarizes methods that can be used to detect leakage of borated reactor coolant during plant operation and during refueling outages
- Regulatory/TS requirements at most plants are:
  - Must be able to detect unidentified leak rates over 1 gpm within 4 hours
  - Two independent leak detection systems must be operable

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Detecting Leakage (continued)

- Industry has committed via NEI 03-08 to meeting requirements in WCAP-16423-NP and WCAP-16465-NP
  - How to determine identified and unidentified leak rates
  - Tighter limits on unidentified leak rates, e.g., 0.3 gpm 1-day leak rate and 0.1 gpm 7-day leak rate
- Full-Scale Mockup Tests support leakage detection by bare metal visual inspections as appropriate to ensure that wastage cavities will not develop sizes that threaten structural integrity
  - Emphasizes value of visual inspections as part of system walkdowns during plant shutdowns and startups
- Capabilities of many different leak detection methods are described and applications where they have been implemented are discussed

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Preventing Leakage and Degradation

- Summarizes methods for minimizing the potential for leaks and corrosion in the event that leakage occurs
  - Main focus is on replaceable seals such as gaskets and packing
- Describes history since 1995 of EPRI programs to help plants develop and implement leakage reduction programs
  - Latest summary is EPRI report 1018959, *Nuclear Maintenance Applications Center: Establishing an Effective Plant Fluid Sealing Technology Program*
  - Other reports that provide guidance on topics such as gaskets, bolting, packing, and mechanical seals are listed

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Preventing Leakage and Degradation (continued)

- Programs directed at minimizing leakage and corrosion associated with flaws in pressure boundary materials:
  - PWSCC
  - Leaks at canopy seal welds
  - ODSCC of stainless steel piping and components
- Methods to minimize corrosion if leakage occurs are described
  - Main focus is use of corrosion resistant bolting; suitable corrosion resistant alloys are listed
  - Other parts that can be replaced also identified, such as clamps for Conoseal joints
  - Use of protective shrouds is noted

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Continued Operation with Leakage and/or Degradation

- Discusses an approach that can be used to continue operation with leakage and/or degradation
  - Emphasizes that main approach should be to stop leak
  - Only use justification for continued operation (JCO) if not practical to stop leak
- Development of JCO involves two pronged approach:
  - Demonstration that all Code requirements will be met despite the corrosion
  - Demonstration that plant safety will be insured by defense-in-depth considerations, e.g., enhanced inspections

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Continued Operation with Leakage and/or Degradation (continued)

- Guidance provided on how to determine extent of current degradation (e.g., by detailed inspections) and how to predict future degradation
  - How to determine the environment that will develop
  - How to establish maximum corrosion rate
- Guidance also provided on:
  - How to evaluate degradation vs. Code requirements, e.g., for corroded bolts, flange corrosion, and vessel wall thinning
  - Establishing inspection requirements
  - How to assess defense-in-depth issues

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Boric Acid Corrosion Control (BACC)

- Main requirements for boric acid corrosion control programs are in WCAP-15988-NP, Rev 1, *Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors*
- Provides an overview and general guidance on main features of an effective BACC plan:
  - Thorough condition monitoring to determine adequacy of current materials and conditions
  - Active leakage reduction program using industry guidance
  - Replacement of susceptible C&LAS parts such as bolts in high risk locations
  - Aggressive PWSCC mitigation program
  - Planned response to leakage events

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