Evaluation of SCC Growth in Low Alloy Steel Vessel Materials in the BWR Environment

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Event Name
Date
Background

- BWRVIP-60 documented current understanding of low alloy steel (LAS) stress corrosion crack (SCC) initiation and SCC growth in the BWR environment in the late 90’s
  - No evidence of SCC initiation in vessel materials exposed to the BWR environment
  - In cases where cracking has been observed due to thermal fatigue, e.g., feedwater nozzle cracking, there has been no evidence of crack extension into the RPV material due to SCC from the fatigue cracks

- In the last 20 years, there have been instances of SCC in nickel-base welds; this has raised concerns about potential crack extension into LAS base material
  - In 1999, extensive cracking was observed in the Alloy 182 shroud support weld at the Tsuruga plant with no extension of the cracks into the LAS base metal
  - Cracking was also observed at the Hamaoka stub tube Alloy 182 weld leading to leakage

- Initial guidance for addressing SCC growth in BWRs was issued following the field cracking; BWR VIP-60-A provided crack growth reference curves and is the currently NRC approved crack growth rates (CGR) basis for LAS in BWR environment.
Cracking in Alloy 182 Attachment welds

Tsuruga BWR/2 Shroud Support Cracking  Hamaoka CRD Stub Tube Weld Cracking
Objective was to provide a methodology for assessment of stress corrosion crack (SCC) growth of low alloy steel (LAS) in BWR reactor pressure vessel (RPV) components

Crack growth rate based on GE film rupture/slip oxidation model

- High sulfur line: \( V = 9.6 \times 10^{-11} \, K^{1.4} \, \text{m/s for K in MPa-√m} \)
- Low sulfur line: \( V = 3.29 \times 10^{-17} \, K^4 \, \text{m/s for K in MPa-√m} \)
- Somewhat limited test data at the time BWRVIP-60-A was issued
- Much of the data included periodic partial unloading (PPU) which was needed to keep the SCC crack growing
- PPU tends to overestimate the growth rate
- The early CGR data had limited instrumentation resolution and the lowest CGR that could be measured was \( 2 \times 10^{-11} \, \text{m/s} \). Since then, the measurement technology has improved and CGRs less than \( 1 \times 10^{-11} \, \text{m/s} \) can be measured reliably
BWRVIP-60-A Disposition Line

Note: 2E-11 m/s ~ 1/2 inch or 12.5 mm in 20 years
Effect of Load Cycling – Periodic Partial Unloading (PPU)

Load cycling tends to overstate CGR; effective CGR decreases with longer hold time.
Since the publication of BWRVIP-60-A in 2003, considerable new field and test data have become available.

A new report, BWRVIP-233, was developed to update the disposition lines contained in BWRVIP-60-A

- Field data on Tsuruga shroud support Alloy 182 weld cracking showed virtual crack arrest at the weld-LAS base metal interface
- Test results with composite Alloy 182/LAS specimens at the Paul Scherrer Institute (PSI) confirmed that cracking in the weld appeared to arrest at the base metal interface
- Test data were based on a combination of constant load and partial period unloading (PPU) with hold times. Separating SCC growth during the hold time and the fatigue crack growth due to stress cycling showed lower crack growth rates as compared to BWRVIP-60-A
- There was also a threshold $K$ level below which SCC growth could not be sustained under steady state conditions
- The CGR for constant $K$ loading was less than the $2\times10^{-11}$ m/s assumed in BWRVIP-60-A
Crack Arrest in Alloy 182/LAS Weld

Effective NWC CGR with Hold Time Correction

CGR without Correction

Effective CGR with Correction
Disposition Lines in BWRVIP-233

Separate NWC CGR for high and low Sulfur content

HWC CGR for all Sulfur contents
Chloride Effects

- Following the publication of BWRVIP-233, concerns arose over the role of low levels of chloride on SCC CGR
- EPRI initiated a test program with GE Global Research Center to assess the effect of low levels of chloride
  - New data from GE GRC and PSI in Switzerland suggested that the CGR can be higher even for low chloride levels (< 5 ppb)
  - Prior BWR Water Chemistry Guidelines Action Level 1 limit was 5 ppb for chloride
- Based on the new data, the Action Level 1 for chloride in the BWR NWC Water Chemistry Guidelines has been reduced from 5 ppb to 3 ppb
Test Data on Chloride Effect

Memory Effect

- When there is an increase in chloride level, the resulting increase in CGR is not immediately realized. There is an incubation and/or activation time. This is referred to as a memory effect.
- EPRI and PSI studies have demonstrated that the effect of a chloride transient is, in fact, not observed immediately in terms of change in CGR.
  - When the chloride transient is over, i.e., normal water chemistry conditions have been restored, the CGR does not return to normal rates immediately. Consequently, there is a time delay.
- In theory, the difference between the recovery time and the incubation time must be added to the transient time for the purpose of crack growth evaluation.
  - The GE GRC data shows that the incubation time is about the same or somewhat longer than the recovery time.
  - Based on this, BWRVIP is taking the position that no additional time needs to be added to the transient time to account for memory effects.
Memory Effect Illustration

Time to Activation (incubation)

Crack Length

Cl

Time to Arrest (recovery)

Crack Length

Cl

SCC#4 of C694 - Low Alloy Steel, PSI SA508, T-L

Pt Potential

CT Potential

Inlet Conductivity

Potential, V or Conductivity, μScm

Crack length, mm

4.9 x 10^-7 mm/s

3 x 10^-7 mm/s

5.4 x 10^-7 mm/s

4 x 10^-7 mm/s

7.9 x 10^-7 mm/s

To 4 g/L Chloride @ 100°F

Stop Chloride @ 100°F

No Liquid Cyclic, 4 g/L Chloride

49.5 MPa/m, 8ppm O_2, 288°C

49.5 MPa/m, 8ppm O_2, 288°C

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CGR for Cl < 3 ppb
CGR for $3 \leq \text{Cl} < 5$ ppb
CGR for Cl ≥ 5 ppb
CGR Monitoring During a Plant Transient

- The Cofrentes BWR had a GE crack arrest verification system with low alloy steel CT specimens.
- The plant experienced a chemistry transient for 48 hours due to condenser leakage.
- Chloride and sulfate exceeded 7 and 9 ppb respectively; conductivity was > 0.3 μS/cm.
- There was a sudden increase in crack length (approximately 3 mils). The CGR was $4.4 \times 10^{-10}$ m/sec, two orders of magnitude lower than the high sulfur line value of $3 \times 10^{-8}$ m/sec at $K= 65$ MPa-$\sqrt{m}$.
- No evidence the effective crack growth period was longer than the transient period; no significant memory effect.
Effect of Chloride in HWC Environment

- Both the GE-GRC and PSI studies confirm the high tolerance to chloride in the HWC environment. No accelerated CGR observed even in 100 ppb chloride.

- Based on the tolerance to chloride under effective HWC (e.g. noble metal chemical addition NMCA) it is concluded that no disposition line needed for chloride under HWC.
Sample Evaluation for Postulated Vessel Cracking

Chloride Transients have Significant Impact on SCC Growth

0.5 inch Vessel Head Crack

0.25 inch Nozzle Crack
Summary and Conclusions

- The crack growth disposition lines originally in BWRVIP-60-A have been updated in BWRVIP-233, Rev. 2 based on additional new test data
  - SCC CGR disposition lines specified for both NWC and HWC. Significantly lower crack growth under HWC conditions
  - Data developed under the new EPRI program showed accelerated SCC growth even for chloride below 5 ppb which was the Action Level 1 limit in the EPRI Water Chemistry Guidelines at that time
  - Since then, the Action Level 1 limit for chloride in the BWR NWC Water Chemistry Guidelines has been reduced from 5 ppb to 3 ppb
  - Crack growth disposition lines recommended for different chloride levels
  - Both the test data confirm the high tolerance to chloride in the HWC environment. No accelerated CGR observed even in 100 ppb chloride

- A draft code case and technical basis document is being prepared and will be presented to the ASME Task Group on Crack Growth Reference Curves in future meetings
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