# Evaluation of Crack Growth Rates for Alloy 690/52/152 and Alloy 600/82/182/132

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**NRC Meeting**
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# Meeting Objective

The objective of this meeting is to present the EPRI MRP report on Alloy 690/52/152 PWSCC crack growth rates and provide clarifications and address comments on the report.

A secondary purpose is to present the EPRI MRP report on Alloy 600/82/182 PWSCC revised crack growth rates.

# Implications of MRP-386 Results

# Relief Requests Expected for Heads with Alloy 690 Nozzles

*Expected Schedule for Submittals, Assuming 20-Year Interval is Requested*

| Unit Order | Replacement Date | Approved Time to Next Inspection | Previously Submitted RRs | Typical Cycle Length | Date of Next Inspection per N-729-4 or Current RR | Date of Next Inspection 20 year Reexamination Interval |
|---|---|---|---|---|---|---|
| 1 | Fall 2006 | 13.0 yr | 1 | 1.5 | Spring 2019 | Fall 2026 |
| 2 | Spring 2010 | 1 Interval | | 1.5 | Fall 2019 | Spring 2030 |
| 3 | Spring 2005 | 15.0 yr | 1 | 2 | Fall 2019 | Fall 2023 |
| 4 | Fall 2009 | 1 Interval | | 1.5 | Spring 2020 | Spring 2029 |
| 5 | Fall 2007 | 13.0 yr | 1 | 1.5 | Fall 2020 | Fall 2026 |
| 6 | Fall 2005 | 15.0 yr* | 2 | 1.5-2.0 | Fall 2020 | Spring 2024 |
| 7 | Spring 2006 | 15.0 yr | 1 | 2 | Fall 2020 | Fall 2024 |
| 8 | Fall 2005 | 15.0 yr | 1 | 1.5 | Fall 2020 | Spring 2025 |
| 9 | Fall 2005 | 15.0 yr | 1 | 1.5 | Fall 2020 | Spring 2025 |
| 10 | Fall 2005 | 15.5 yr | 2 | 1.5 | Spring 2021 | Fall 2025 |
| 11 | Spring 2006 | 15.0 yr | 2 | 1.5 | Spring 2021 | Fall 2025 |
| 12 | Fall 2005 | 15.5 yr | 2 | 1.5 | Fall 2021 | Spring 2026 |
| 13 | Spring 2006 | 16.0 yr | 1 | 2 | Spring 2022 | Spring 2026 |
| 14 | Spring 2003 | 15.0 yr | 1 | 1.5 | Spring 2022 | Fall 2026 |
| 15 | Spring 2007 | 15.0 yr | 1 | 1.5 | Spring 2022 | Fall 2026 |
| 16 | Spring 2003 | 1 Interval | | 2 | Spring 2022 | Spring 2032 |
| 17 | Fall 2011 | 1 Interval | | 2 | Spring 2022 | Spring 2030 |
| 18 | Spring 2003 | 1 Interval | | 1.5 | Fall 2022 | Fall 2031 |
| 19 | Fall 2003 | 1 Interval | | 2 | Fall 2022 | Fall 2032 |

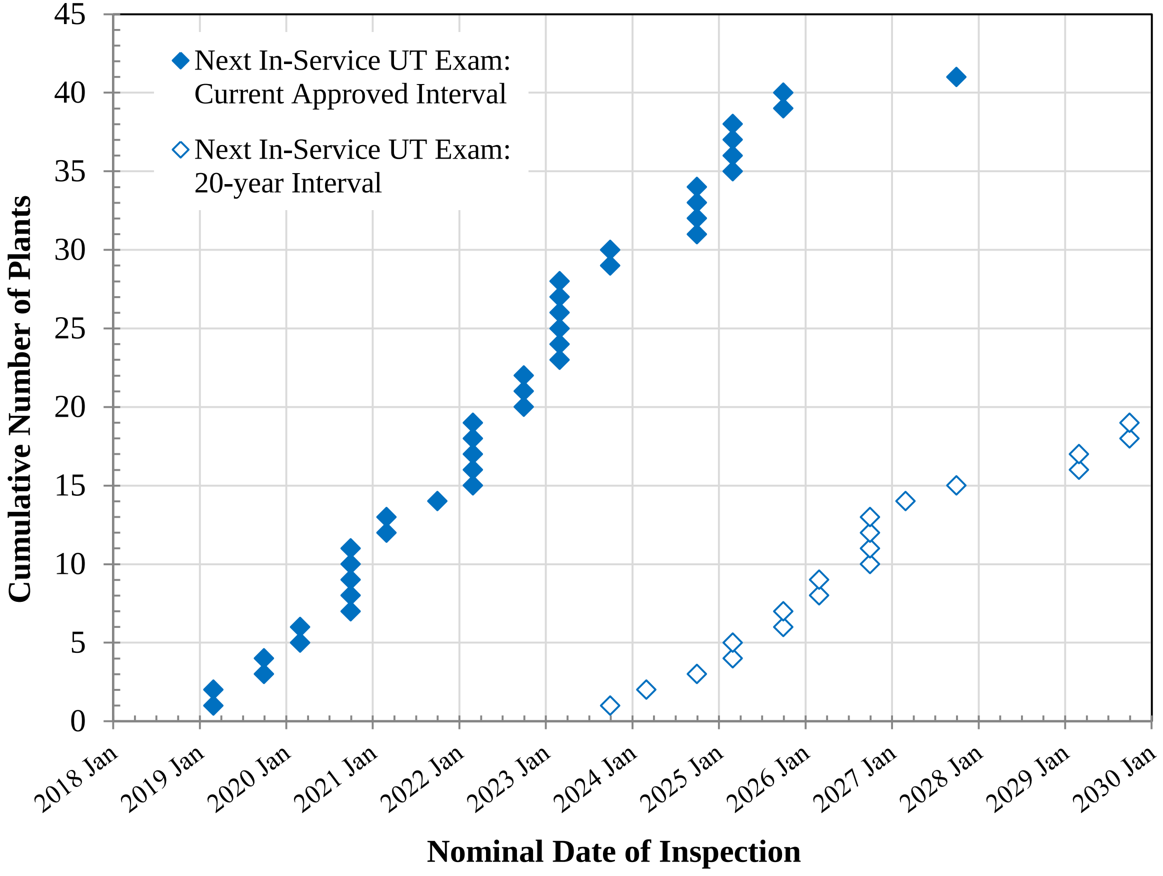
* Second relief request is pending

| Unit Order | Replacement Date | Approved Time to Next Inspection | Previously Submitted RRs | Typical Cycle Length | Date of Next Inspection per N-729-4 or Current RR | Date of Next Inspection 20 year Reexamination Interval |
|---|---|---|---|---|---|---|
| 20 | Spring 2003 | 1 Interval | | 1.5 | Fall 2022 | Fall 2031 |
| 21 | Spring 2007 | 16.0 yr | 1 | 2 | Spring 2023 | Spring 2027 |
| 22 | Spring 2008 | 15.5 yr | 1 | 1.5 | Spring 2023 | Fall 2027 |
| 23 | Spring 2005 | 1 Interval | | 1.5 | Spring 2023 | Spring 2032 |
| 24 | Fall 2003 | 1 Interval | | 1.5 | Spring 2023 | Spring 2032 |
| 25 | Fall 2003 | 1 Interval | | 1.5 | Spring 2023 | Spring 2032 |
| 26 | Spring 2013 | 1 Interval | | 1.5 | Spring 2023 | Spring 2032 |
| 27 | Spring 2004 | 1 Interval | | 2 | Fall 2023 | Fall 2033 |
| 28 | Fall 2003 | 1 Interval | | 2 | Fall 2023 | Fall 2033 |
| 29 | Fall 2004 | 1 Interval | | 1.5 | Fall 2024 | Fall 2033 |
| 30 | Fall 2005 | 1 Interval | | 1.5 | Fall 2024 | Fall 2033 |
| 31 | Fall 2009 | 16.0 yr | 1 | 1.5 | Fall 2024 | Spring 2029 |
| 32 | Spring 2005 | 1 Interval | | 1.5 | Fall 2024 | Fall 2033 |
| 33 | Spring 2005 | 1 Interval | | 1.5 | Spring 2025 | Spring 2034 |
| 34 | Fall 2005 | 1 Interval | | 1.5 | Spring 2025 | Spring 2034 |
| 35 | Fall 2014 | 1 Interval | | 1.5 | Spring 2025 | Spring 2034 |
| 36 | Spring 2010 | 16.0 yr | 1 | 1.5 | Spring 2025 | Fall 2029 |
| 37 | Fall 2004 | 1 Interval | | 1.5 | Fall 2025 | Fall 2034 |
| 38 | Fall 2010 | 16.0 yr | 1 | 1.5 | Fall 2025 | Spring 2030 |
| 39 | Spring 2017 | 1 Interval | | 1.5 | Fall 2027 | Fall 2036 |

# Relief Requests Expected for Heads with Alloy 690 Nozzles

*Expected Schedule for Submittals, Assuming 20-Year Interval is Requested*

- Relief requests previously submitted:
  - 21 relief requests for 18 heads have been approved to date for alternative intervals up to 16 calendar years
  - One second relief request proposing an interval of 15 years is under consideration
- Assuming relief requests are submitted one year before the outage, the number of expected relief requests is:
  - Spring 2019: 6
  - Spring 2020: 13
  - Spring 2021: 19
  - Spring 2022: 28
  - Spring 2023: 30
  - Spring 2024: 38



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# FOI Implications for Inlays/Onlays

- Current regulatory situation:
  - Code Case N-770-2 specifies that all inlays/onlays at a plant be examined on a sample basis
  - The current NRC condition would require examination every 10 years for all hot leg nozzles
  - Approval for crediting inlays/onlays has not been granted by NRC even with the 50.55a condition because a FOI of 10 does not support 10 years for hot leg nozzles nor 40 years for cold leg nozzles
- MRP-386 draws the following conclusion regarding diluted Alloy 52/152, with Cr of at least 24%:
  - "Section 4.7.4 concluded that Alloy 52/152-type materials with Cr contents down to 24% have similarly low susceptibility to PWSCC as welds with the nominal Alloy 52/152 Cr content of at least 28%. Therefore, although there are limited scored data at the lower Cr contents such that the full FOI of 324 may not be appropriate to apply at this time, the available data do support crediting the much improved CGR behavior (i.e., much lower CGRs) of diluted Alloy 52/152 down to 24% Cr compared to Alloy 82/182/132."
- The laboratory CGR data support FOIs much greater than 10 for Alloys 52/152, including interfaces, and support increased credit for inlays/onlays

# ASME Code Case N-729-5, -6

- Scope
  - Alloy 690/52/152 nozzles and welds in replacement heads and new PWRs
- Current Status
  - Volumetric examination performed every 10 years has been shown to be overly conservative based on plant experience and laboratory testing
- Volumetric examination performed per proposed alternative interval requirements:
  - Alternative interval requirements allow 20-year intervals
  - Removes excess conservatism while maintaining a conservative approach
  - Ensures an acceptably small impact of PWSCC on nuclear safety
  - In combination with the visual examination requirements, conservatively addresses the concern for leakage
  - Ensures that information on the status of the U.S. fleet of heads with Alloy 690 nozzles continues to be collected
  - Continues to provide reasonable assurance of structural integrity and thus an acceptable level of quality and safety

# FOI Implications for Heads with Alloy 690 Nozzles

- The minimum FOIs needed for Alloy 690/52/152 to justify an inspection interval equivalent to the required Alloy 600/82/182 interval of RIY=2.25 were calculated (ML14237A256)
- Implied FOI is equivalent to the ratio of RIY accumulated during the requested interval to RIY=2.25
  - For a head operating at **605°F**, the RIY after 20 years with a capacity factor of 98% is 22.2 and the needed **FOI is 9.9**
  - For a head operating at **613°F**, the RIY after 20 years with a capacity factor of 98% is 27.0 and the needed FOI is **12.0**
- MRP-386 concluded that FOIs of 38 and 324 were appropriate for Alloy 690 and Alloy 52/152, respectively, both of which provide considerable bounding margin for the needed FOI of 12
- Subsequent analyses for weld interface data also support a 20-year interval, with the aggregate FOI for interface data for each laboratory being greater than 12

# Factors of Improvement for Alloy 690 and Alloy 52/152 PWSCC CGRs

*Materials Reliability Program: Recommended Factors of Improvement for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) Growth Rates of Thick-Wall Alloy 690 Materials and Alloy 52, 152, and Variants Welds (MRP-386).* EPRI, Palo Alto, CA: 2017. 3002010756.

https://www.epri.com/#/pages/product/000000003002010756/

# Topics of NRC Comment at Environmental Degradation Conference 2017 and Tampa Meeting 2017

1. Interpretation of Periodic Partial Unloading Data
2. Treatment of Cold Worked Material
3. Weld Interface and Dilution Zone Testing
4. Parameter Dependencies
5. Heat-to-Heat Variation / Data Scatter
6. Low Crack Growth Rate Data
7. Welds
   a) Residual strain
   b) Repairs
8. Heat-Affected Zones
9. Future Data

# Interpretation of Periodic Partial Unloading Data

Comment

- Effects of periodic partial unloading (PPU) are not sufficiently understood, so it is uncertain whether the data should be used in analytical models
- Possible approaches include:
  - Include all PPU data (most conservative but potentially unrepresentative)
  - Exclude all PPU (simplifies analysis but potentially increases model uncertainty)
  - Include PPU only if they meet certain criteria (e.g., hold time, duration, etc.)

Resolution

- Addressed in Section 2.4.2 and Appendix D.2
- PPU data were excluded from the CGR database
  - Effect is often large and not well characterized
  - Most PPU data have adjacent constant load data under the same conditions
  - Extensive time and effort to compile and score all PPU data was considered too large of an effort for too little of a return

# Treatment of Cold Worked Material

Comment

- Cold work (CW) level should be included in CGR models, although simply specifying % thickness reduction will likely not be adequate
- Cold work levels in plant components should be appropriately evaluated, including variation in initial internal strain/hardness and unintentional noncompliance with ASME/vendor requirements

Resolution

- Addressed in Sections 4.2.3 and 5.1
- 12% CW was selected as a conservative best-fit (~75$^{th}$ percentile) value based on ex-service A600 materials and A690 mockups
- 12% CW was converted to 600 MPa YS, as YS includes residual stresses from fabrication that are not accounted for by the added CW level
- Two Alloy 690 databases were used for the FOI investigation to compare the effects of having a 12% CW vs. 600 MPa YS limit (15 data point difference)

# Weld Interface and Dilution Zone Testing

Comment

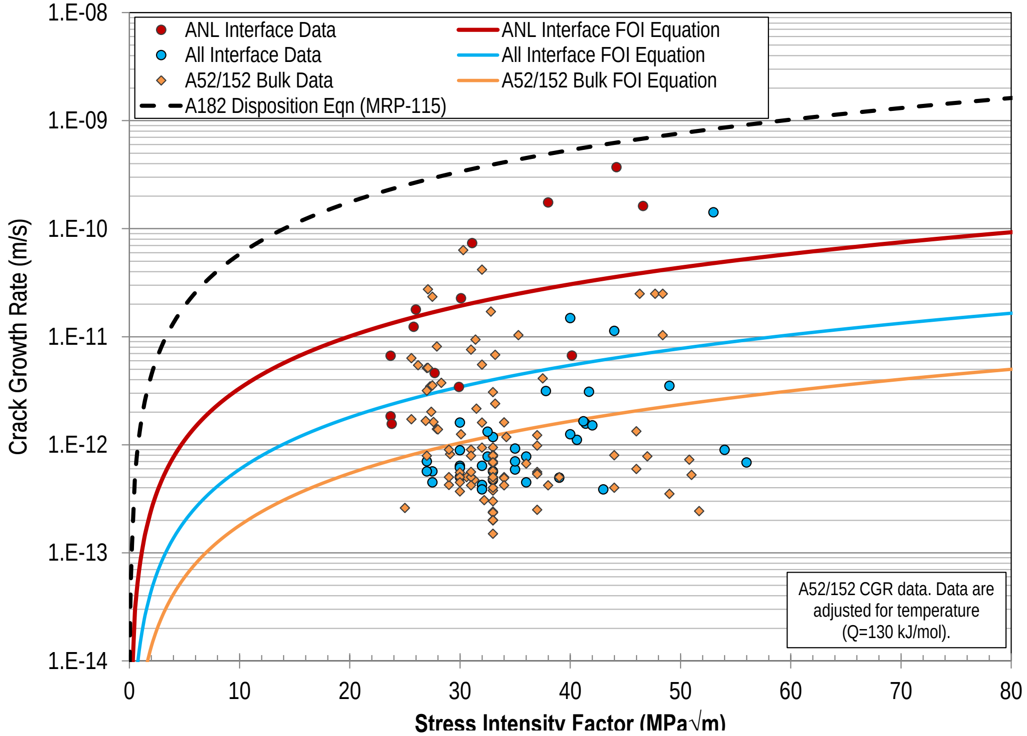
- Susceptibility of dilution zone (DZ) is likely affected by type of interface and welding parameters
- Microstructural features, such as localized high strain boundaries, could play an important role, but they are not well understood

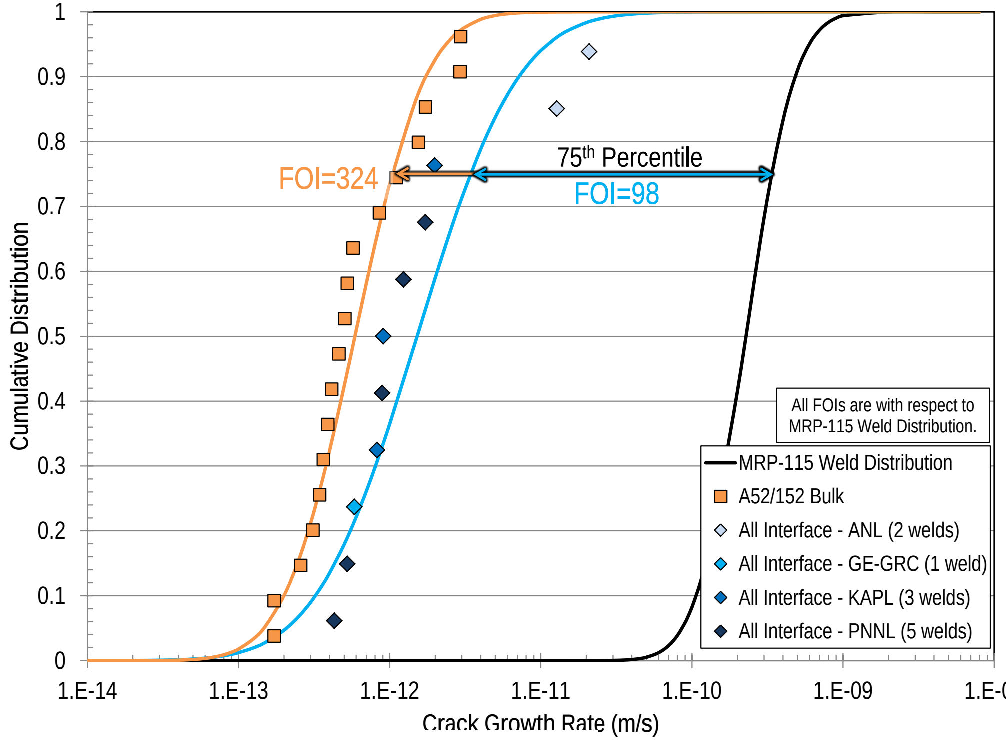
Resolution

- Addressed in Section 4.7.4 and Appendix G.7
- The Expert Panel decided that there were insufficient data available at the time to predict CGRs specific to Alloy 52/152 dilution zones/weld interfaces due to the wide variety of interface types and limited data for each (50 total points, 6 interface types)
- Instead, these sections describe the chromium dilution levels expected (based on mockups) and include data from the Environmental Degradation Conference 2017 (Toloczko) that show that there is generally no through-wall leak path through high strain boundaries

# Weld Interface and Dilution Zone Testing (cont.)

- Recent Argonne National Laboratory (ANL) report (NUREG/CR-7226; Jan 2018) presents weld interface data
- A subsequent analysis was performed to compare the factors of improvement (FOIs) for these ANL interface data, all compiled interface data, and the bulk weld data (Used same method of analysis as for Alloy 690 and bulk Alloy 52/152)




NB: The interface data and plots have not been reviewed by the Expert Panel.

# Parameter Dependencies

Comment

- Using dependencies obtained from high-CW materials necessitates the assumption that the values are appropriate for low-CW materials also
- There is a high degree of scatter in results of similar materials

Resolution

- Addressed in Section 5 and Appendix H
- Recommending an FOI that was developed using the MRP-55 and MRP-115 parameters, rather than the parameter values determined from the Alloy 690/52/152 data, eliminates the concern regarding uncertainties with precise parameter values
- Comparison of the preliminary parameter values for A690 (often developed from high-CW materials) with those for A600 (generally from low-CW materials) suggests that extrapolation of the values from high-CW to low-CW data is reasonable

# Heat-to-Heat Variation / Data Scatter

## Comment

- CGRs evolve during a single test segment
- Large differences in CGRs across heats and even within heats across laboratories is observed
- Most important aspect to understand of PWSCC response is microstructural and mechanical properties of material (e.g., grain size, precipitate distribution, banding)

## Resolution

- Addressed in Section 5 and Appendix K
- Long-term CGR is reported if it evolves over a test segment
- 75$^{th}$ percentile of heat factors is used for the FOI development, and no-growth data is excluded from plant-relevant database

# Low Crack Growth Rate Data

## Comment

- CGRs less than ~$1x10^{-12}$ m/s approach the resolution and detectability limits of laboratories
- Some laboratories have reported that certain parameter effects (e.g., temperature) are not observed at very low CGRs

## Resolution

- Addressed in Section 5
- CGRs <$1x10^{-12}$ m/s were not adjusted for temperature when determining the statistical distribution of heat factors, from which the recommended FOI was determined

# Welds

## *Residual Strain*

- Addressed in Section 4.6 and Appendix G.6
- EPRI MRP sponsored a study of residual plastic strain in Alloy 690/52/152 weld mockups
- Similar to MRP-115 approach for Alloy 82/182, no adjustments were made to correct for the amount of strain in the original weld or in the machined specimen
- Electron backscatter diffraction (EBSD) results from several labs have shown that while local high strain regions exist, the chances that they will form a through-wall leak path are very low

# Welds

## *Defects*

- Addressed in Section 4.7 and Appendix G.5
- Several mockups with defects were tested
  - 2 excavate and weld repair mockups
  - 2 ductility dip mockups
  - 1 refuse mockup
- All specimens tested from these mockups exhibited low CGRs ($<5 \times 10^{-12}$ m/s)

# Heat-Affected Zones

- Addressed in Section 4.2.3
- The residual strains measured in the Alloy 690 heat-affected zone (HAZ) influenced the cold work limit used for the FOI database
- Conservative best-fit (~75$^{th}$ percentile) of HAZ strains was ~12%

# Future Data Recommended by Expert Panel

- Addressed in Appendix C
- This appendix lists the data gaps and testing priorities suggested for future work
  - Heat-to-heat variation, particularly for low-CW wrought Alloy 690 materials
  - More data obtained under specific and plant-relevant testing conditions (i.e., ≤12% CW) could confirm that dependencies obtained from high-CW data accurately extrapolate to plant-relevant conditions with sufficient confidence to produce a disposition equation for application to plant components
  - More weld DZ data would facilitate better understanding of PWSCC behavior in those regions
- Newly generated Alloy 690/52/152 data will be compiled as appropriate

# Implications of MRP-420 Results

# Ongoing Assessment of MRP-420 Results

- EPRI is currently sponsoring work to evaluate the implications of the MRP-420 results for both MRP- and non-MRP guidance
  - Alloy 600 thick-wall wrought material and Alloy 82/182 weld material
  - Locations such as Alloy 600 reactor vessel closure head penetrations, Alloy 600 instrument nozzles, and Alloy 82/182 piping butt welds

# Questions?

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