Assessment of Laboratory PWSCC Crack Growth Rate Data for Nickel-Based Alloys

Amanda R. Jenks and Glenn A. White
Dominion Engineering, Inc.

Paul Crooker
Electric Power Research Institute

International Light Water Reactor Materials Reliability Conference and Exhibition 2016
August 1-4, 2016
Outline

- Introduction
- Expert Panel
- Data Assessment
- Applicable Material Conditions
- Model Development
Introduction

- An international PWSCC Expert Panel has been organized by EPRI to support the development of equations for predicting crack growth rates (CGRs) due to PWSCC of Ni-based alloys
- A total of over 1200 CGR data points from 11 international laboratories for Alloys 690/52/152 and 600/82/182 have been compiled
- A significant portion of the available crack growth rate data was produced by national laboratories under sponsorship of the U.S. NRC, and NRC staff input has been considered in planning for this Expert Panel effort
- Results from this research will be used to:
  - Inform regulatory consideration of inspection relief
  - Develop guidelines for material procurement to maximize PWSCC resistance
  - Qualify new weld metal formulations with regard to PWSCC resistance
  - Incorporate flaw disposition curves for base and weld metals into codes and standards for use in flaw evaluations
Objectives and Work Scope

- **Objectives:**
  - Produce equations for predicting PWSCC CGRs in Alloys 690, 52, and 152
  - If warranted, revise the CGR disposition curves in MRP-55 and MRP-115 for Alloys 600 and 82/182, respectively, to consider the data that were not included in the original publication

- **Work Scope:**
  - Compile and evaluate constant load CGR data for Alloys 690/52/152 and 600/82/182
  - Perform statistical analyses on CGR data to develop PWSCC CGR models and determine effects of various factors (e.g., temperature, cold work, heat treatment)
  - Develop positions/recommendations for numerous technical topics that were not addressed in MRP-55 and MRP-115 (HAZ, CW, heat treatment, low K)
  - Produce an EPRI report detailing the data, CGR equations, further analysis, and methodology
Expert Panel

- The Expert Panel is comprised of 14 members with international expertise in PWSCC research and industry experience, with subgroups for Data Evaluation and Application experts

- Data Evaluation Experts have experience testing PWSCC growth in laboratory settings; their task is to evaluate the generated data from a purely testing perspective
  - Members: Stuart Medway (AMEC), Bogdan Alexandreanu (ANL), Denise Paraventi (BMPC-Bettis), F.J. Perosanz and Lola Gomez-Briceño (CIEMAT), Peter Andresen (GE-GRC), Mychailo Toloczko (PNNL)

- Application Experts have experience with industry occurrences of PWSCC; their task is to relate laboratory testing conditions to plant conditions and guide the statistical analysis for the development of CGR equations
  - Members: Steve Fyfitch (AREVA), Dave Morton (BMPC-KAPL), Raj Pathania (EPRI), Pål Efsing (Ringhals), Anders Jenssen (Studsvik), Toshio Yonezawa (Tohoku), Warren Bamford (Westinghouse)
Data Collection

- **Data Collected**
  - Over 750 CGR data points for Alloys 690/52/152 and weld interface material
    - Over 350 specimens, 71 heats, 8 laboratories
  - Over 500 CGR data points for Alloys 600/82/182 material
    - Over 350 specimens, 37 heats, 10 laboratories
    - This is in addition to the data that were included in MRP-55 and MRP-115

- Supplementary information, such as crack length vs. time (a-vs-t) plots and fractography, have been collected for all specimens when available to support scoring by the Data Evaluation Group

- Materials property data and post-supplier processing information have been compiled when available to support evaluation by the Applications Group
Data Assessment

- Data are evaluated before being used in the statistical analysis to enhance the quality of the resulting CGR models.
- Rather than using hard threshold criteria for screening, as were applied in MRP-55 and MRP-115, the Data Evaluation Experts are scoring each Alloy 690/52/152 data point on the basis of credibility from a testing standpoint using expert judgment.
- Several guidelines were developed to aid in scoring, including:
  - The reported CGR can be determined in one of several ways by the primary investigator, but it can be reevaluated at other Experts’ request to enhance consistency.
  - Because of the low PWSCC susceptibility of Alloy 690/52/152, there is no minimum crack increment needed for a test segment to be included, but low crack increment and low CGR data are screened carefully.
  - Cracks do not necessarily have to be intergranular (IG) – i.e., transgranular (TG) growth is not automatically disqualified – but having sufficient opportunity to grow IG is necessary.
  - No implications on applicability to plant material conditions is intended with this scoring.
  - Only constant load (CL) data will be scored because of the large and inconsistent effect of periodic partial unloading (PPU).
Data Assessment – Example

Overview - c372 - Alloy 690, 26%RA 1D, S-L Orientation, NX3297HK12, ANL

Corrected Data

Outlet conductivity x 0.01

Est. pH at 360°C = 8.2 used for \( f_c \)
At 340°C, pH = 7.53. At 300°C, pH = 6.86

GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 841 32 360 26 600 1 0.98 100 100 1.07 5.70E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 1186 34 360 26 600 1 0.72 100 100 1.07 2.80E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 652 35 325 10.4 600 1 0.48 100 100 1.07 2.80E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 1145 35 290 4.3 600 1 1.5 100 100 1.07 2.80E-07

GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 841 32 360 26 600 1 0.98 100 100 1.07 5.70E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 1186 34 360 26 600 1 0.72 100 100 1.07 2.80E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 652 35 325 10.4 600 1 0.48 100 100 1.07 2.80E-07
GE-GRC c372 NX3297HK12 MA+26%CR plate Special Metals S-L 1145 35 290 4.3 600 1 1.5 100 100 1.07 2.80E-07

Data from GE-GRC
SCC#7 - c372 - Alloy 690, 26%RA 1D, S-L Orientation, NX3297HK12, ANL

c372 - 0.5TCT of 690 + 26%RA 1D, 360C
34 MPa/m, 600 B / 1 Li, 26 cc/kg H₂

Outlet conductivity x 0.01

To R=0.7, 0.001 Hz +
9000s hold @ 1540h
To Constant K
@ 1635h

1.9 x 10⁻⁷
mm/s

1.74 x 10⁻⁷

1.70 x 10⁻⁷

4.01 x 10⁻⁸

9.18 x 10⁻⁸

2.92 x 10⁻⁷

Est. pH at 360C = 8.2 used for \( \phi_c \)
At 340C, pH = 7.53. At 300C, pH = 6.86

After ~1.2 mm of growth by cyclic loading

Data Assessment – Reported CGR

Data from GE-GRC
Data Assessment – Minimum Crack Increment

- Because transitioning from the fatigue precrack to SCC was rarely done, a minimum crack increment of 0.5 mm was required for Alloy 82/182 data used in MRP-115, and any “no growth” data was considered meaningless.

- At a rate of $1E^{-7}$ mm/s (75th percentile CGR for Alloys 600 and 82 at 30 MPa√m and 325°C), it would only take about 1400 hours (~2 months) for the crack to grow 0.5 mm.

- For the scored, as-received Alloy 690 data adjusted to 30 MPa√m and 325°C, the 75th percentile CGR is $1E^{-9}$ mm/s; at this rate, it would take 15 years for the crack to grow to 0.5 mm.

- DCPD monitoring systems have improved to be able to detect very low growth, often down to $1E^{-10}$ mm/s, which along with the application of transitioning load steps, has increased confidence in these low growth rates for highly resistant materials.

- Low crack increments without long test times may be cause for a lower score by some experts, but they are not summarily eliminated from the database.
Data Assessment – Transitioning

- The load sequence for PWSCC CGR tests includes several steps:
  - Machine a notch into a CT specimen
  - Fatigue the specimen to grow the crack away from the machined notch
  - Add periodic hold times during fatigue (i.e., periodic partial unloading, PPU)
  - Apply constant load/constant K

- This process is known as “transitioning” the TG fatigue crack to an IG SCC crack at constant load

- Significant, well-behaved growth should occur during each transitioning step
Data Assessment – Fracture Morphology

- The goal of transitioning is to let the crack find a susceptible grain boundary location so it can grow intergranularly as is typical for PWSCC
- Sometimes, however, the microstructure of the material is sufficiently resistant to PWSCC that the IG path is not consequentially more susceptible than the TG path
- Partially- or fully-TG cracks are not necessarily penalized during scoring, provided there was sufficient transitioning to allow enough time and distance for the crack to become IG
Data Assessment – Fracture Morphology (cont’d)

- Cracks in weld materials typically grow along the dendrites
- Occasionally, particularly at weld interfaces, a crack may grow off-plane, which could result in less accurate DCPD measurements of crack growth
- The method of addressing off-plane growth is under discussion by the Expert Panel
Applicable Material Conditions

- Ni-base alloys are used for partial penetration welded (i.e., J-groove) nozzles in existing and new plants and piping safe ends in new plants.

- The material conditions tested in the laboratory are not always directly comparable to those used for plant components.

- Applicability considerations include:
  - Added cold work
  - Orientation
  - Product form
  - Weld interface (base metal HAZ, weld dilution zones, etc.)

- Regardless of material applicability, all data will be used to develop full CGR models that incorporate a full range of effects; it will subsequently be simplified to an equation that is applicable to plant conditions.
Applicable Material Conditions – Cold Work

- Cold work (CW) is often added to Alloy 690 wrought materials as an accelerating factor to produce measurable CGRs in test periods of months rather than years.
- Over 90% of compiled Alloy 690 data has some degree of added CW, primarily with 10-30% thickness reduction.
- While it is generally accepted that while there is no intentional CW introduced to plant components, it is possible for 10-15% CW to be unintentionally added, such as by:
  - Incomplete annealing
  - Straightening after thermal treatment
  - Welding
- Alloy 690 steam generator tube plugs, which may have large amounts of intentionally introduced cold work, and steam generator divider plates are not included in this analysis.
- Direct effects of added CW, as well as secondary effects (e.g., yield strength and hardness increases), on CGRs are being investigated to be included in the CGR model.
Applicable Material Conditions – Orientation

- CT specimens can be oriented in one of six ways and can be described in terms of orientation vs. product form or orientation vs. deformation
- Analyses of the relative effects of orientation vs. product form and orientation vs. deformation are being performed for various levels of cold work
- Product form orientations implying laminar cracks in wrought Alloy 690 material are highly improbable in service and so are not directly relevant:
  - S-L and S-T orientations in plate material
  - R-L and R-C orientations in CRDM nozzle material
- For welds, the vast majority of testing has been performed in the T-S direction (along the dendrites), particularly for Alloy 52/152, so limited orientation effects can be investigated
Periodic Partial Unloading

- Periodic partial unloading (PPU) is used in SCC tests primarily as a transitioning step when advancing from a fatigue pre-crack to constant load/constant K.
- It has also been used as a means of validating SCC CGRs by assuming a superposition model and subtracting out the air fatigue and corrosion fatigue growth rate components:
  \[ \dot{a}_{\text{env}} = \dot{a}_{\text{air}} + \dot{a}_{\text{CF}} + \dot{a}_{\text{SCC}} \]
- The approach of reporting SCC growth rates based on adjustment of PPU data is not generally supported by the Data Evaluation experts because of the concern for using expectation rather than observed results, but this approach is used by one laboratory.

![Diagram showing the stages of fatigue, periodic partial unloading, and constant load in SCC testing.](image-url)
Periodic Partial Unloading (cont’d)

- PPU data with hold times >1 hr were included in the MRP-55 and MRP-115 databases for Alloys 600 and 82/182, respectively, because it had been determined that longer hold times did not significantly affect CGRs for these materials as compared to those for constant load/constant K (CL/CK) data.

- The Expert Panel decided that while PPU data is useful data to have, only CL/CK data will be used for this effort to determine PWSCC CGR equations for Alloy 690/52/152.

- Reasons for not including the PPU data in the modeling database include:
  - There is clear evidence that PPU accelerates CGRs in Alloy 690/52/152, but unlike Alloy 600/82/182, there is no clear hold time beyond which CGRs are not significantly affected and the acceleration factors can be large and variable (5-30x).
  - Only a limited amount of PPU data has been compiled, and obtaining the remainder would require a very significant effort, particularly as there is at least 2-3x the amount of PPU data obtained during any given test as CL/CK data.
Data Scoring

- Each Alloy 690/52/152 data point is given two scores to separate the quality of the test itself from the confidence in the reported CGR for that segment, especially for low CGRs
  - Column 1 Score: Test Segment Credibility
  - Column 2 Score: CGR Uncertainty
- Scores are assigned from 1 (best) to 5 (worst) by each Data Evaluation Expert and are subsequently averaged into an aggregate score
- Data with a Column 1 aggregate score of 3 or better will be used in the model development, although the effects of this cutoff will be investigated
- Column 2 scores are primarily a reminder that low CGRs are less precise than medium/high CGRs due to the typically insufficient growth to be confirmed fractographically; they may be used as a weighting factor during model development or included in some other way
Model Development

- Effects of individual variables via specific subsets of data are being investigated, in addition to a general regression analysis incorporating the interactions of multiple variables.
- Specific subsets of the database, including on-the-fly studies with single specimens, will be used for evaluating individual effects.
  - For example, temperature effects (activation energy) can be determined using data with the same heat, cold work level, and K value.
- Full CGR models will include terms for various conditions, such as K, temperature, cold work/hardness/yield strength, orientation, and alloy (for welds).
- The form of the CGR equations for all alloys is expected to be similar to those developed in MRP-55 and MRP-115.
- The MRP-55 and MRP-115 equations are being evaluated for the need to be updated with current analyses considering the original data as well as new data that was not included originally.
  - Possible changes include:
    - Adjustment or removal of 9 MPa√m K threshold for Alloy 600.
    - Inclusion of CW/YS/hardness term for all alloys.
    - Inclusion of a factor to credit exposure to PWHT of adjacent carbon or low-alloy steel.
  - The original and new data are generally consistent, so substantial changes to the equations are not expected over most of the range in K.
Together…Shaping the Future of Electricity